HIRT

Hybrid Impedance-Resistivity Tomography System

Complete Technical Whitepaper

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

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HIRT Development Team

Version: 2.0 | **Date:** January 2026

This document contains 20 sections covering all aspects of HIRT system design, construction, operation, and applications.

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Section 0: Index

Hybrid Impedance-Resistivity Tomography System - Whitepaper Index

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

About This Document

This whitepaper provides complete documentation for the HIRT system, a hybrid geophysical survey tool combining Magnetic Induction Tomography (MIT) and Electrical Resistivity Tomography (ERT) for subsurface imaging in forensic, archaeological, and environmental applications.

Key Applications

- **WWII bomb crater investigation** - UXO assessment and burial detection
- **Woodland burial search** - Clandestine grave detection under tree cover
- **Wetland/swamp surveys** - Subsurface mapping in challenging terrain

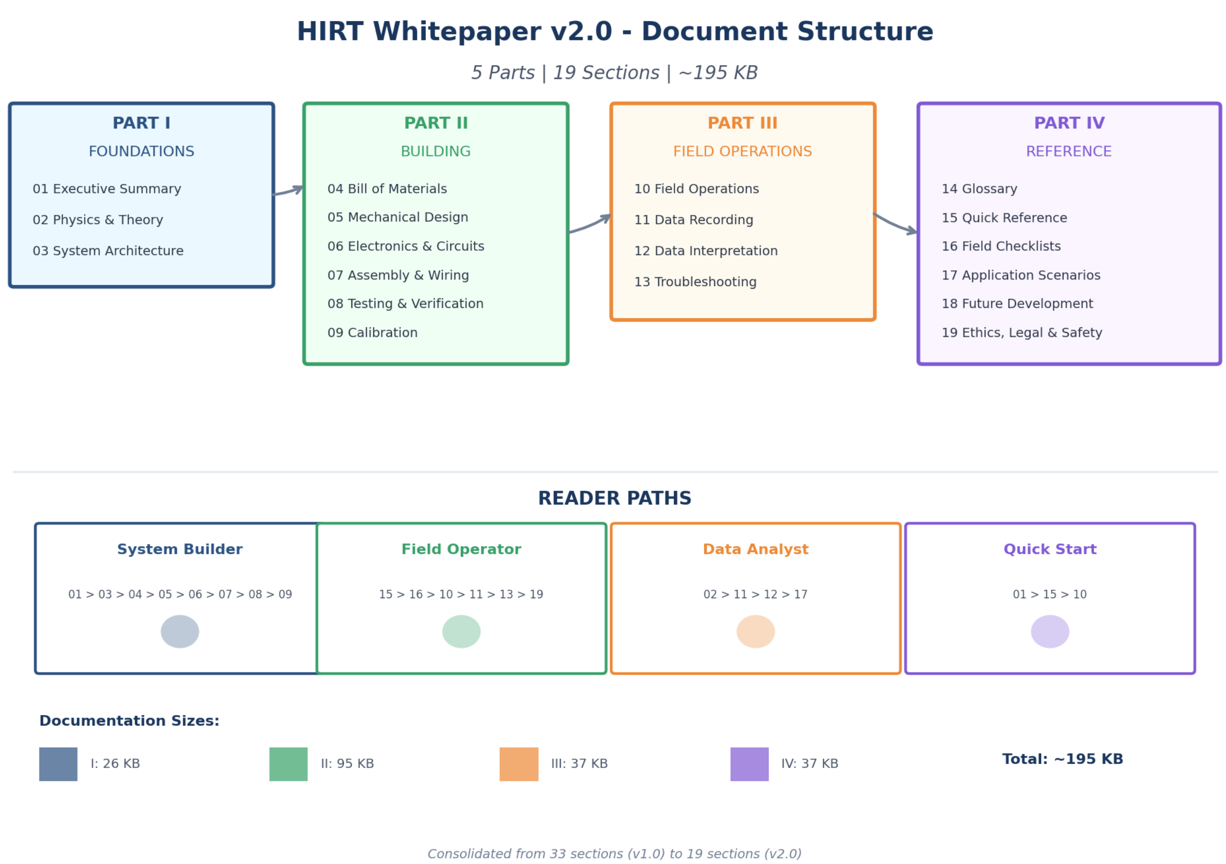

Figure 1. HIRT Whitepaper v2.0 document organization. The whitepaper is divided into 5 parts containing 19 sections, with recommended reader paths for different user roles. Total documentation size is approximately 195 KB, consolidated from the original 33-section v1.0 structure.

Part I: Foundations

The Foundations part introduces the HIRT system, its theoretical basis, and overall architecture. These sections provide essential context for understanding the system design.

#	Section	Description
01	Executive Summary	What is HIRT, use cases, capabilities, target audience
02	Physics & Theory	MIT and ERT principles, frequency selection, measurement geometry
03	System Architecture	Micro-probe design, centralized hub, array configurations

Table 1. Part I: Foundations - 3 sections, ~26 KB

Part II: Building

The Building part provides comprehensive instructions for constructing a complete HIRT system. These sections should be followed sequentially when building a new system from components.

#	Section	Description
04	Bill of Materials	Complete BOM with costs ($1,800-3,900), part numbers, suppliers
05	Mechanical Design	Rod segments, coils, ERT rings, junction box, 3D prints, CAD
06	Electronics & Circuits	MIT circuit, ERT circuit, power, complete schematics
07	Assembly & Wiring	Step-by-step assembly, wiring diagrams, waterproofing
08	Testing & Verification	Test procedures, QC checklist, pass/fail criteria
09	Calibration	Coil, TX, RX, ERT calibration; field quick-check; schedule

Table 2. Part II: Building - 6 sections, ~95 KB

Part III: Field Operations

The Field Operations part covers deployment, data collection, and troubleshooting in the field. These sections are essential references for field operators.

#	Section	Description
10	Field Operations	Planning, grid design, installation, measurement protocols
11	Data Recording	MIT/ERT file formats, probe registry, metadata
12	Data Interpretation	Resolution, detection limits, combined analysis
13	Troubleshooting	Diagnostics, repairs, when to abort

Table 3. Part III: Field Operations - 4 sections, ~37 KB

Part IV: Reference

The Reference part contains supplementary materials including glossary, quick reference cards, checklists, detailed application scenarios, and important safety and ethical considerations.

#	Section	Description
14	Glossary	Acronyms and terminology
15	Quick Reference	Printable field card
16	Field Checklists	Pre/on-site/post deployment checklists
17	Application Scenarios	Detailed playbooks for crater, woods, swamp
18	Future Development	Software roadmap, hardware improvements, manufacturing status
19	Ethics, Legal & Safety	Permits, UXO protocols, conductivity monitoring

Table 4. Part IV: Reference - 6 sections, ~37 KB

Section Dependencies

The following diagram illustrates the relationships between sections and recommended reading sequences. Solid arrows indicate primary dependencies (prerequisite reading), while dashed arrows show cross-references.

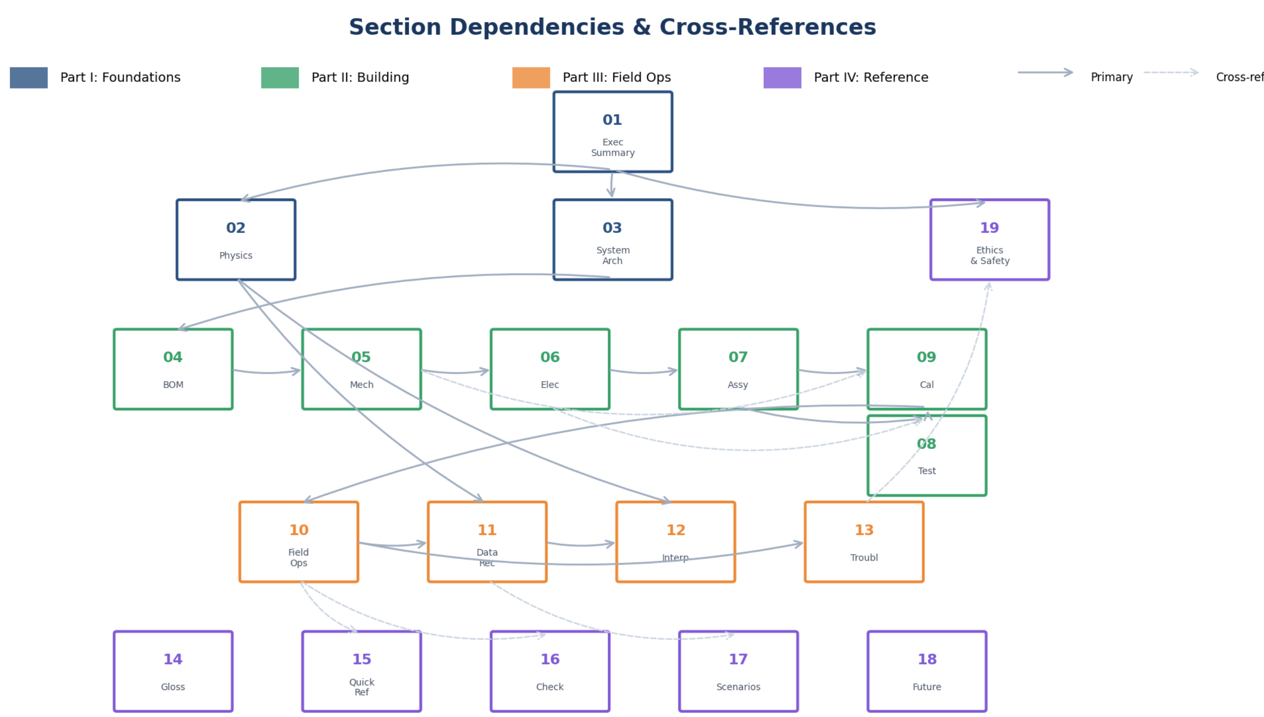

Figure 2. Section dependency map showing primary reading sequences (solid arrows) and cross-reference relationships (dashed arrows). Colors indicate the part each section belongs to. The Build sequence (04-09) is typically followed linearly, while Reference sections (14-19) can be accessed independently as needed.

Reader Paths

Different users should follow different paths through the documentation based on their role and objectives:

Path A: System Builder

For building a HIRT system from scratch, follow this sequence: 01 Executive Summary (overview) -> 03 System Architecture (understand design) -> 04 Bill of Materials (order parts) -> 05 Mechanical Design (manufacture components) -> 06 Electronics & Circuits (assemble PCBs) -> 07 Assembly & Wiring (integration) -> 08 Testing & Verification (quality control) -> 09 Calibration (prepare for deployment).

Path B: Field Operator

For operating an existing HIRT system: 15 Quick Reference (keep on hand) -> 16 Field Checklists (pre-deployment) -> 10 Field Operations (detailed procedures) -> 11 Data Recording (data formats) -> 13 Troubleshooting (when issues arise) -> 19 Ethics, Legal & Safety (UXO sites).

Path C: Data Analyst

For processing and interpreting HIRT data: 02 Physics & Theory (understand measurements) -> 11 Data Recording (format specs) -> 12 Data Interpretation (analysis methods) -> 17 Application Scenarios (interpretation context).

Path D: Quick Start

Minimal reading for experienced users: 01 Executive Summary (5 min overview) -> 15 Quick Reference (field card) -> 10 Field Operations (detailed if needed).

Quick Topic Lookup

Use this reference table to quickly locate information on specific topics:

Topic	Primary Section	Related Sections
Coil winding	05 Mechanical Design	09 Calibration
Current source (ERT)	06 Electronics	08 Testing
Data formats	11 Data Recording	12 Interpretation
DDS/TX circuit	06 Electronics	09 Calibration
Frequency selection	02 Physics	10 Field Ops
Grid layout	10 Field Operations	15 Quick Reference
Lock-in detection	06 Electronics	02 Physics
Part numbers	04 Bill of Materials	-
PCB layout	06 Electronics	07 Assembly
Probe insertion	10 Field Operations	05 Mechanical
QC checklist	08 Testing	16 Checklists
Reciprocity	09 Calibration	12 Interpretation
Ring electrodes	05 Mechanical	06 Electronics
Schematics	06 Electronics	04 BOM
Skin depth	02 Physics	12 Interpretation
STL files	05 Mechanical	18 Future Dev
Time-lapse	19 Ethics/Safety	10 Field Ops
UXO safety	19 Ethics/Safety	10 Field Ops

Table 5. Quick topic lookup for common subjects across the whitepaper

Document Conventions

File Naming

Section files follow the format **XX-topic-name.md** where XX is the section number (00-19). All filenames use lowercase with hyphens.

Cross-References

Internal links use the format [Section Title](XX-filename.md). Section references in text follow the pattern: 'See Section 10: Field Operations'.

Measurement Units

- **Length:** meters (m), millimeters (mm)
- **Frequency:** kilohertz (kHz), hertz (Hz)
- **Current:** milliamps (mA), microamps (uA)
- **Resistance:** ohms, kilohms (k-ohm), megohms (M-ohm)
- **Conductivity:** microsiemens/cm (uS/cm)

Version History

Version	Date	Changes
2.0	2026-01	Consolidated from 33 to 19 sections
1.0	2025-01	Complete whitepaper package (33 sections)
0.9	2024-12	Manufacturing release (16mm modular design)
0.5	2024-11	Initial documentation structure

Table 6. Document version history

This is the master index for the HIRT whitepaper v2.0. All 19 sections are contained in the docs/whitepaper/sections/ directory.

Section 1: Executive Summary

HIRT Overview, Capabilities, Target Audience, and Cost Comparison

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

1.1 What is HIRT?

HIRT (Hybrid Inductive-Resistivity Tomography) is a **dual-channelsubsurface imaging system** designed for archaeological and forensic investigations. By placing sensors inside the ground and measuring through the volume using **crosshole geometry**, HIRT obtains true tomographic coverage for 3D reconstruction of subsurface features.

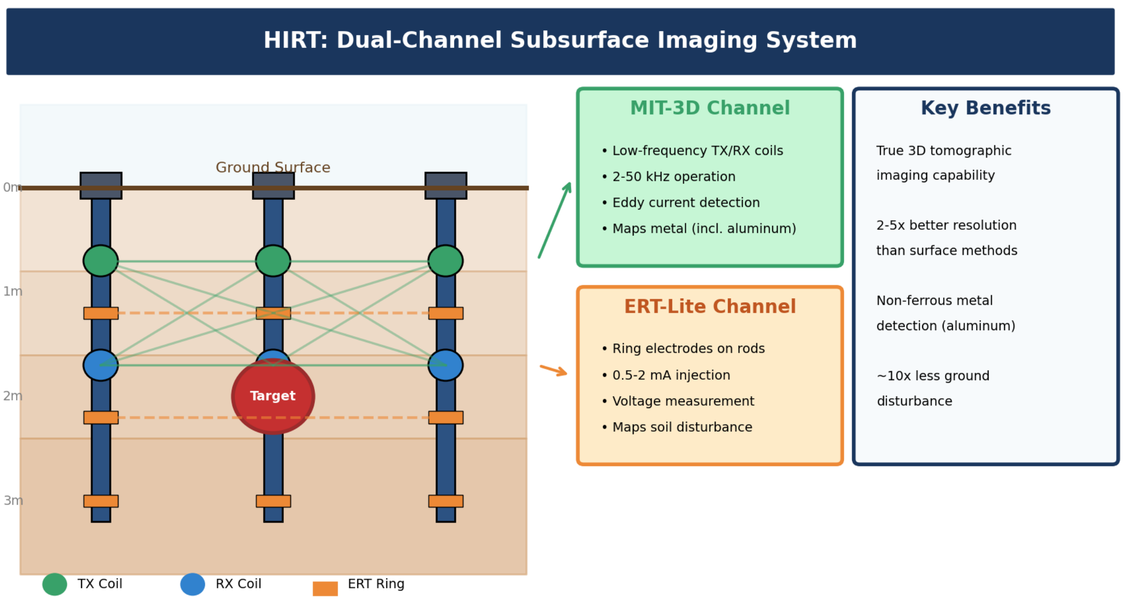

Figure 1. HIRT dual-channel system overview. The system combines MIT-3D (Magneto-Inductive Tomography) for metal detection with ERT-Lite (Electrical Resistivity) for soil disturbance mapping. Probes are inserted into pre-drilled 18-20mm holes, with ray paths traversing the target volume for true 3D tomographic imaging.

1.2 Why the Name

HIRT was created in a landscape shaped by war and unfinished consequences.

The Silesian basin of modern-day Poland was the target of one of the most intensive Allied bombing campaigns of World War II, centered on the Blechhammer industrial complex. Tens of thousands of bombs fell here. Many exploded. Thousands did not. Today, an estimated 4,000–6,000 unexploded bombs remain buried beneath forests, wetlands, and towns, still capable of detonation decades later. These UXOs continue to shape land use, infrastructure planning, and public safety across the region.

This same ground holds other histories. POW camps and forced labor sites. Jewish victims of the industrial death system tied to Blechhammer. Aircrews lost in the bombing campaigns. Civilians—families and children—killed not as targets, but by proximity. After the war came displacement, silence, and redevelopment layered over danger that was never fully removed.

My great-uncle, 1st Lt. Arthur Lindell, was shot down here. He and his crew are still missing, believed to lie in a filled bomb crater at the crash site. That search is personal—but it exists within a much larger, unresolved problem shared by communities across Europe and beyond.

HIRT takes its name from this history of hurt and pain, and from a commitment to address what remains beneath the surface. It was designed to see without excavation, to reduce risk where danger still exists, and to help bring clarity—whether the goal is safety, remembrance, or recovery.

1.3 Dual-Channel Approach

HIRT employs two complementary sensing modalities that together provide comprehensive subsurface characterization:

- **MIT-3D (Magneto-Inductive Tomography):** Low-frequency TX/RX coils (2-50 kHz) measure amplitude and phase changes caused by eddy currents. Maps conductive metal masses including aluminum, which magnetometry cannot detect.
- **ERT-Lite (Electrical Resistivity):** Small ring electrodes inject tiny currents (0.5-2 mA) and measure voltage distribution. Maps soil resistivity variations from moisture, disturbance patterns, voids, and grave shafts.

Design Philosophy

- Make each probe dual-role (TX & RX for MIT) plus ERT pickup
- Identical probes simplify logistics and improve data quality
- Modular, interchangeable components for field serviceability
- Minimal site disturbance (~10x less than traditional methods)

1.4 Primary Use Cases

HIRT is optimized for three primary application scenarios, each with specific configuration recommendations:

Use Case	Typical Parameters	Key Method	Target Types
Filled Bomb Crater	10-15m dia, 0-4m depth 3m probes, 1.5m spacing	MIT + ERT combined	Metal parts + remains
Woods Burials	0.6-1.5m depth 1.5m probes, 1m spacing	ERT patterns + MIT	Grave shafts, artifacts
Swamp/Wetland	>5m targets, margins Low-freq MIT	MIT from margins	Deep targets

Table 1. Primary HIRT use cases and configurations

1.5 System Capabilities

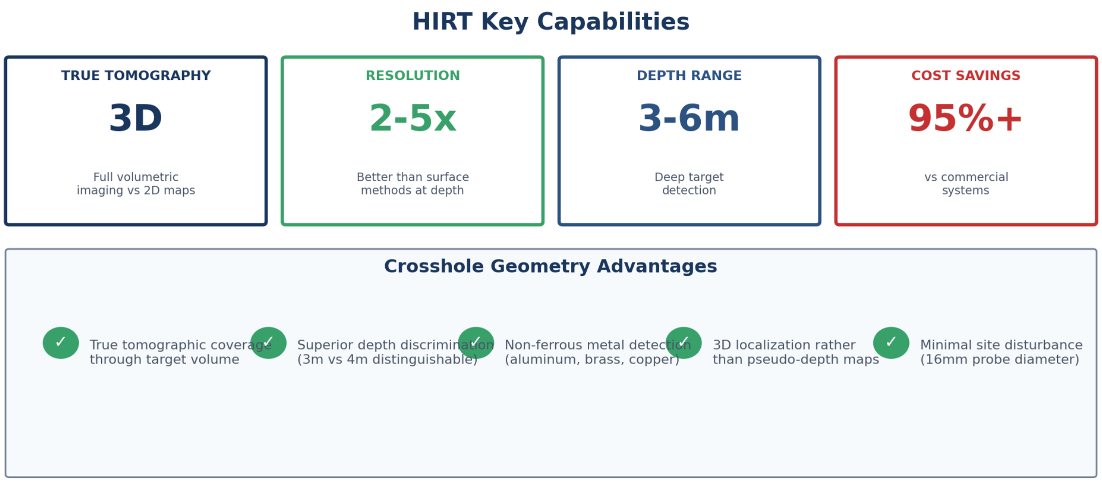

Figure 2. Key HIRT capabilities infographic. The crosshole geometry provides true 3D tomographic imaging with 2-5x better resolution than surface methods at depths exceeding 2 meters. Cost savings of 95%+ make professional-grade subsurface imaging accessible to research institutions and humanitarian organizations.

Surface GPR and magnetometry are excellent screening tools but can yield ambiguous results in complex conditions. HIRT's crosshole geometry provides superior performance through direct measurement paths:

- **True tomographic coverage** through the target volume (not surface extrapolation)
- **2-5x better resolution** than surface methods at depths exceeding 2 meters
- **Superior depth discrimination** - targets at 3m vs 4m are clearly distinguishable
- **Non-ferrous detection** - aluminum aircraft parts that magnetometry cannot sense
- **3D localization** with measured positions rather than estimated pseudo-depth

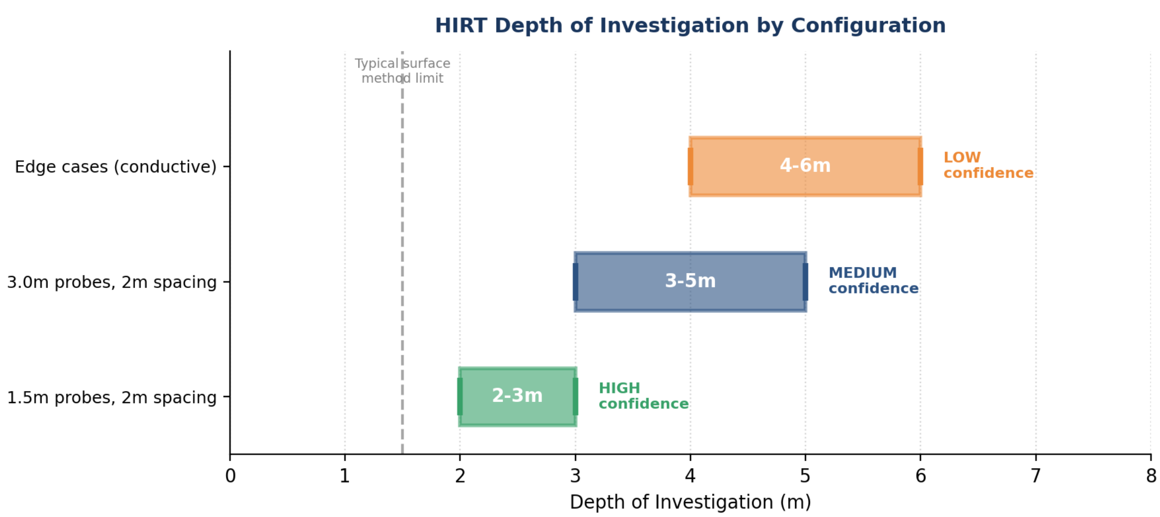

Figure 3. Depth of investigation ranges by HIRT configuration. The typical surface method limit (~1.5m) is shown for comparison. Confidence levels indicate the reliability of detection at different depths and soil conditions.

1.6 Limitations and Non-Goals

Non-Goals

- Producing final 3D visuals (software pipeline is a separate development phase)
- Replacing standard ethical/excavation practices or permits
- Replacing professional archaeological/forensic protocols

When Surface Methods Remain Superior: Rapid large-area screening (10x faster), shallow targets (<1m) where GPR resolution excels, purely ferrous targets (magnetometry), and initial site characterization before targeted investigation.

Technical Limitations: Smaller coil area results in ~19 dB SNR loss compared to commercial systems (compensated by longer integration times). Survey time increases 5-10x compared to commercial systems. Requires post-processing software for 3D reconstruction. Limited depth performance in highly conductive soils.

1.7 Optimal Workflow

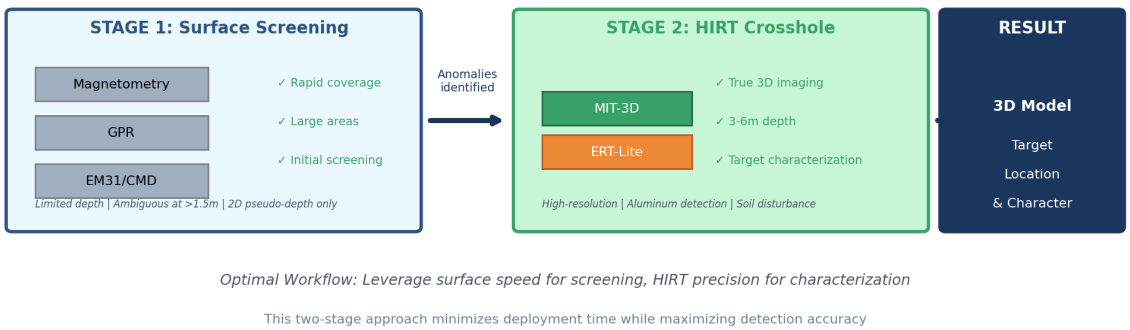

Figure 4. Two-stage optimal workflow combining surface screening methods with HIRT crosshole follow-up. This approach leverages the speed of surface methods for initial anomaly identification, then applies HIRT's superior resolution for detailed characterization of identified targets.

The physics supports a **two-stage approach** that leverages the strengths of both surface and crosshole methods:

1. **Surface screening** (magnetometry, GPR, EM31): Identify anomalies quickly over large areas with rapid coverage rates.
2. **HIRT crosshole follow-up**: Characterize identified anomalies with superior 3D resolution and depth discrimination.

1.8 Target Audience

This documentation and the HIRT system are designed for:

- **Archaeologists** investigating WWII sites, burial locations, or crash sites
- **Forensic investigators** requiring non-destructive subsurface imaging
- **Geophysicists** interested in low-cost tomographic methods
- **DIY builders** seeking to construct field-deployable systems
- **Researchers** exploring crosshole electromagnetic/resistivity techniques

1.9 Cost Overview

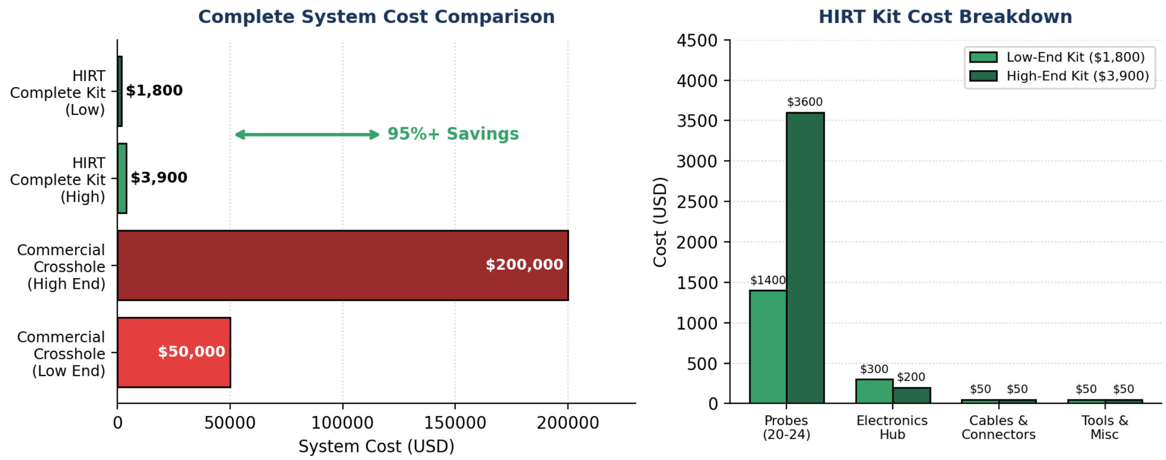

Figure 5. Cost comparison between HIRT and commercial crosshole systems. A complete HIRT starter kit costs $1,800-3,900 depending on component selection, representing 95%+ savings compared to commercial systems ($50,000-200,000+). The primary cost driver is the number of probes (20-24 for standard deployment at $70-150 each).

Component	Low-End	High-End	Notes
Probes (20-24)	$1,400	$3,600	$70-150 per probe
Electronics Hub	$300	$200	DIY vs pre-built
Cables & Connectors	$50	$50	Standard components
Tools & Misc	$50	$50	Assembly tools
Total	$1,800	$3,900	95%+ vs commercial

Table 2. HIRT system cost breakdown

This cost structure places professional-grade subsurface imaging capabilities within reach of university research groups, non-profit humanitarian organizations, and archaeological teams that could not otherwise afford crosshole tomography.

Section 2: Physics Theory

Electromagnetic and Galvanic Principles for Subsurface Imaging

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

2.1 Overview

The HIRT system combines two complementary geophysical sensing modalities: Magneto-Inductive Tomography (MIT-3D) and Electrical Resistivity Tomography (ERT-Lite). Understanding the physics underlying each method is essential for proper system deployment, frequency selection, and data interpretation. This section provides a practical, field-level treatment of the relevant physics principles.

2.2 MIT-3D (Low-Frequency Electromagnetic)

2.2.1 Operating Principle

MIT-3D uses oscillating magnetic fields to detect conductive anomalies in the subsurface. A transmit (TX) coil drives a stable sinusoidal current at frequencies between 2-50 kHz, generating a primary magnetic field. When this field encounters conductive material—such as metal objects or high-conductivity soil zones—it induces eddy currents within the conductor.

These eddy currents generate a secondary magnetic field that opposes the primary field. Receive (RX) coils positioned at known distances from the TX coil measure the combined field. The presence of conductive targets manifests as measurable changes in both the **amplitude** and **phase** of the received signal relative to the transmitted waveform.

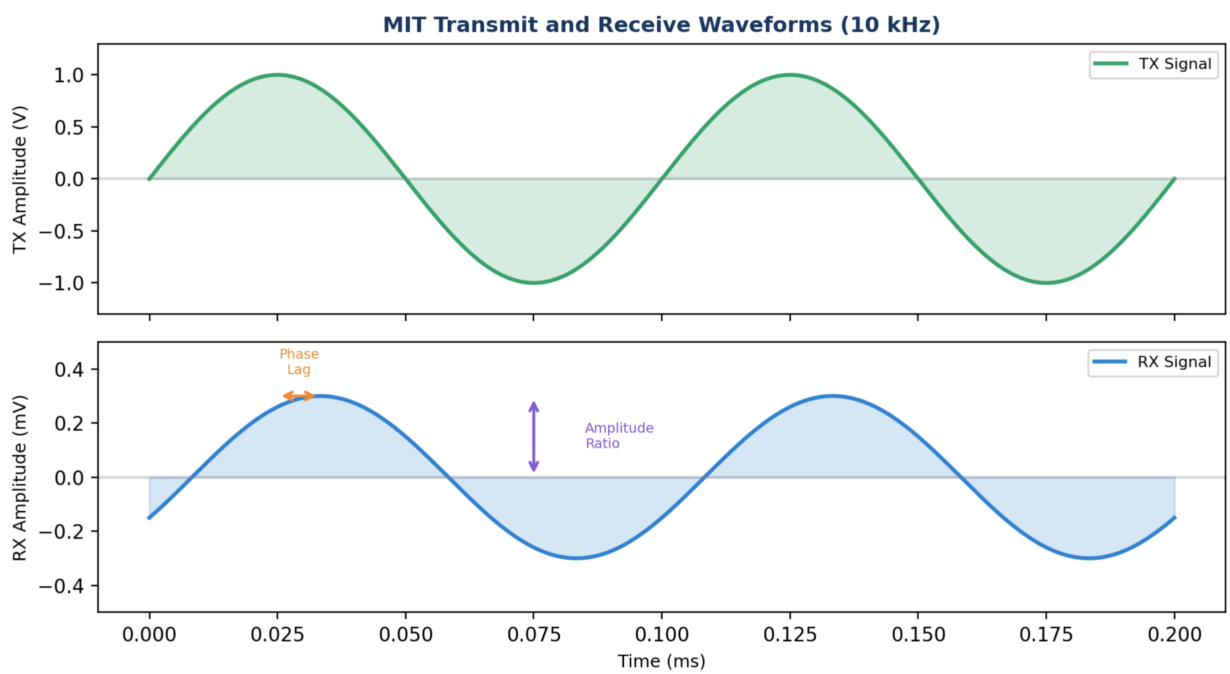

Figure 1. TX and RX waveform comparison at 10 kHz. The transmitted signal (top) induces a received signal (bottom) that is both attenuated and phase-shifted. The amplitude ratio and phase lag encode information about the conductivity and geometry of subsurface targets along the TX-RX path.

2.2.2 Frequency Selection

Operating frequency determines the trade-off between depth penetration and near-surface sensitivity:

- **Lower frequency (2-10 kHz)**: Deeper penetration, better for targets at 2.5-4+ meters
- **Higher frequency (20-50 kHz)**: Sharper sensitivity near probes, better for 0.5-1.5 meter targets
- **Multi-frequency sweep**: Recommended for unknown target depths; provides spectral discrimination

Target Depth	Recommended Frequencies	Integration Time
0.5-1.5 m (shallow)	20-50 kHz	1-3 sec
1.5-2.5 m (mid-range)	10-20 kHz	3-5 sec
2.5-4 m (deep)	2-10 kHz	5-15 sec
>4 m (very deep)	2-5 kHz	10-30 sec

Table 1. Target-dependent frequency selection guidelines. Higher frequencies provide sharper near-surface resolution while lower frequencies enable deeper penetration. Longer integration times improve SNR at all frequencies.

2.3 Electromagnetic Skin Depth

Electromagnetic skin depth (δ) defines how deeply alternating EM fields penetrate into conductive media before being attenuated to 1/e (~37%) of their surface value. This fundamental parameter is given by:

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

where $\omega = 2\pi f$ is the angular frequency, $\mu = \mu_0\mu_r$ is the magnetic permeability (typically $\mu_0 = 4\pi\times10^{-7}$ H/m for non-magnetic soils), and σ is the electrical conductivity in S/m.

Conductivity (S/m)	2 kHz	5 kHz	10 kHz	20 kHz	50 kHz
0.01 (dry sand)	112 m	71 m	50 m	35 m	22.5 m
0.1 (moist sand)	35.6 m	22.5 m	15.9 m	11.2 m	7.1 m
0.5 (wet clay)	15.9 m	10.1 m	7.1 m	5.0 m	3.2 m
1.0 (saturated clay)	11.2 m	7.1 m	5.0 m	3.6 m	2.3 m

Table 2. Skin depth values for typical soil conductivities across the HIRT operating frequency range. Even in the most conductive soils, skin depth exceeds typical investigation depths at HIRT frequencies.

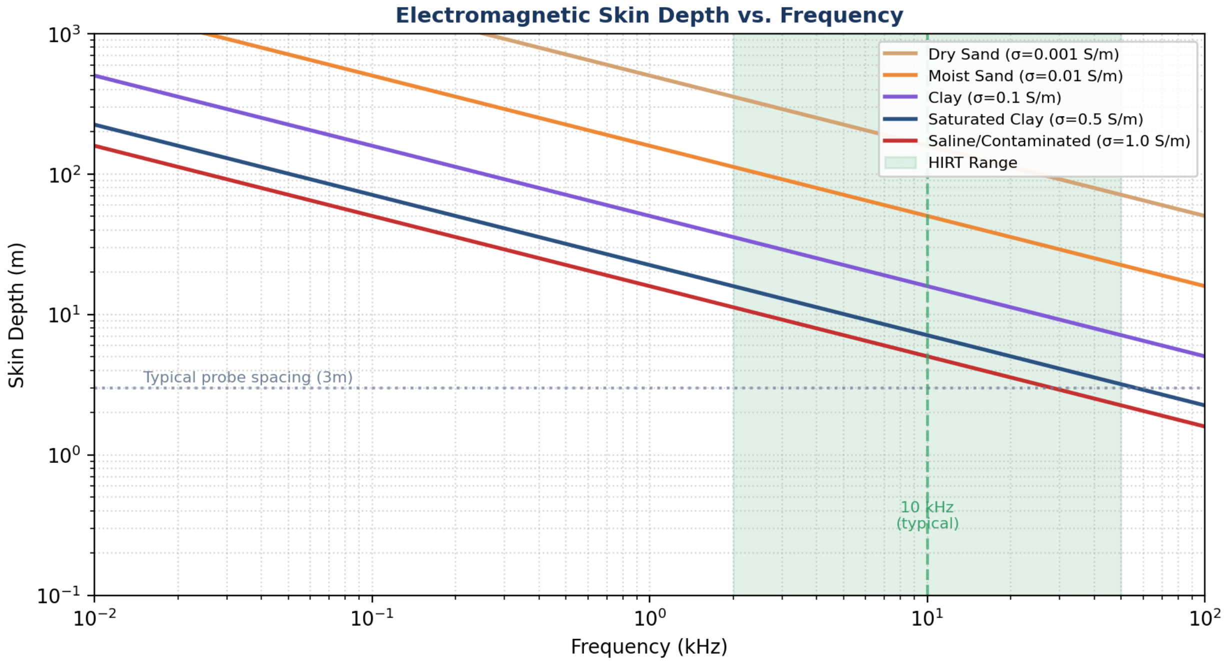

Figure 2. Electromagnetic skin depth versus frequency for five soil types spanning the conductivity range from dry sand (0.001 S/m) to saline/contaminated soil (1.0 S/m). The green shaded region indicates the HIRT operating range (2-50 kHz). The dashed line marks 10 kHz, a typical operating frequency.

KEY INSIGHT: Skin Depth vs. Coupling Geometry

- Skin depth alone does NOT limit MIT investigation depth in most field conditions
- Even in saturated clay at 50 kHz, skin depth (2.3 m) exceeds typical probe spacing
- The practical depth limitation is coil coupling geometry (1/r^3 decay), not skin depth
- Effective MIT depth is approximately 1-2x probe spacing in near-field conditions

2.4 MIT Coil Coupling and 1/r^3 Decay

In the near-field regime where HIRT operates, the magnetic field coupling between TX and RX coils decays as the cube of the separation distance. This $1/r^3$ relationship is the fundamental limitation on MIT investigation depth—not electromagnetic skin depth.

The magnetic dipole field strength at distance r from a coil is proportional to $1/r^3$ for the near-field component (which dominates at distances much less than the wavelength). For a round-trip measurement (TX to target to RX), the sensitivity can decay as fast as $1/r^6$ depending on target geometry.

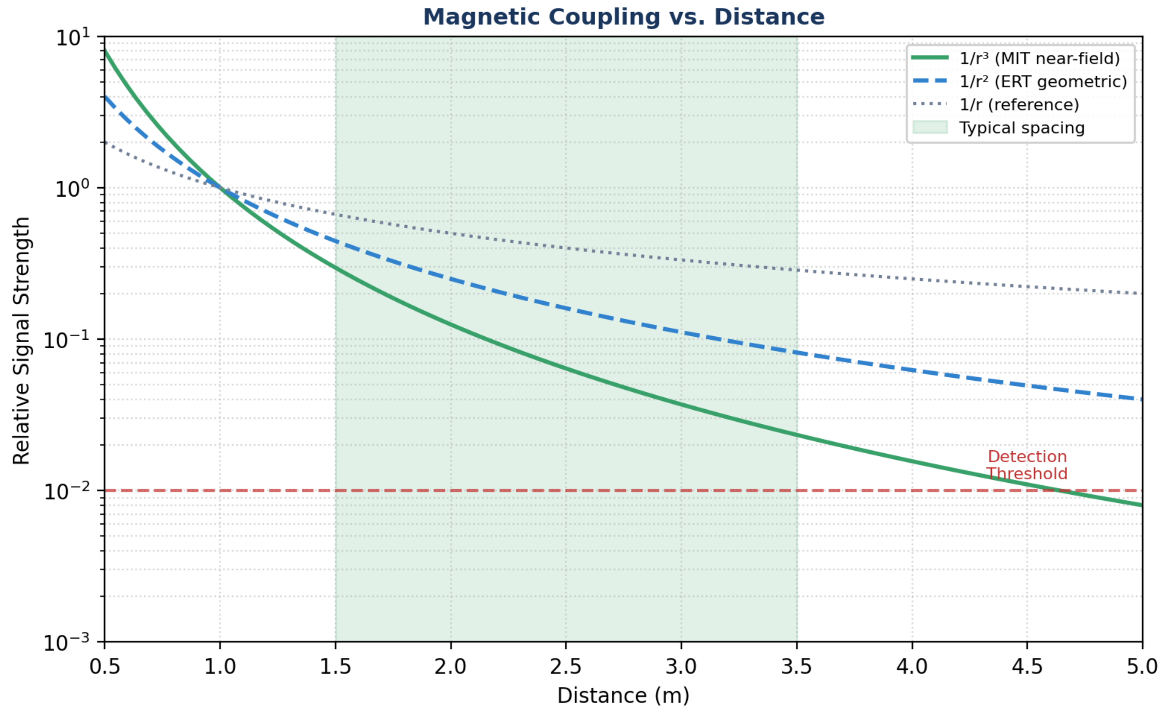

Figure 3. Magnetic coupling decay versus distance. The MIT near-field coupling (1/r^3) decays much faster than ERT geometric spreading (1/r^2). The green shaded region indicates typical HIRT probe spacing (1.5-3.5 m). Signal strength drops below practical detection thresholds beyond ~4-5 m separation.

This rapid decay has important implications for system design:

- **Probe spacing**: Maximum useful TX-RX separation is ~3-4 m for typical targets
- **Array density**: Dense probe arrays (1-2 m spacing) provide better coverage than sparse arrays
- **Signal processing**: High dynamic range ADCs required to capture both strong and weak paths
- **Integration time**: Longer measurement integration needed for distant TX-RX pairs

2.5 ERT-Lite (Galvanic Method)

2.5.1 Operating Principle

Electrical Resistivity Tomography injects electrical current through the subsurface and measures the resulting voltage distribution. Two electrodes inject a known current (typically 0.5-2 mA for safety), while other electrodes measure voltage differences. The ratio V/I, combined with the electrode geometry, yields the apparent resistivity ρ_a of the material between electrodes.

Unlike MIT, ERT does not respond to metallic targets directly. Instead, it detects **resistivity contrasts** such as disturbed fill, moisture variations, compacted layers, voids, and the boundaries of burial pits. The combination of MIT (metal-sensitive) and ERT (structure-sensitive) provides comprehensive target characterization.

2.5.2 Geometric Factor K

The geometric factor K converts measured V/I ratios to apparent resistivity:

$$\rho_a = K \times (V / I)$$

For HIRT's borehole electrode geometry, the geometric factor is approximately:

$$K \approx \pi \times L$$

where L is the separation distance between current injection electrodes.

Configuration	L (electrode separation)	K
A(0.5m) to B(1.5m)	1.0 m	3.14 ohm-m
A(0.5m) to C(2.5m)	2.0 m	6.28 ohm-m
A(0.5m) to D(3.0m)	2.5 m	7.85 ohm-m

Table 3. ERT geometric factors for HIRT ring electrode configurations. Larger electrode separations provide greater depth of investigation but lower resolution.

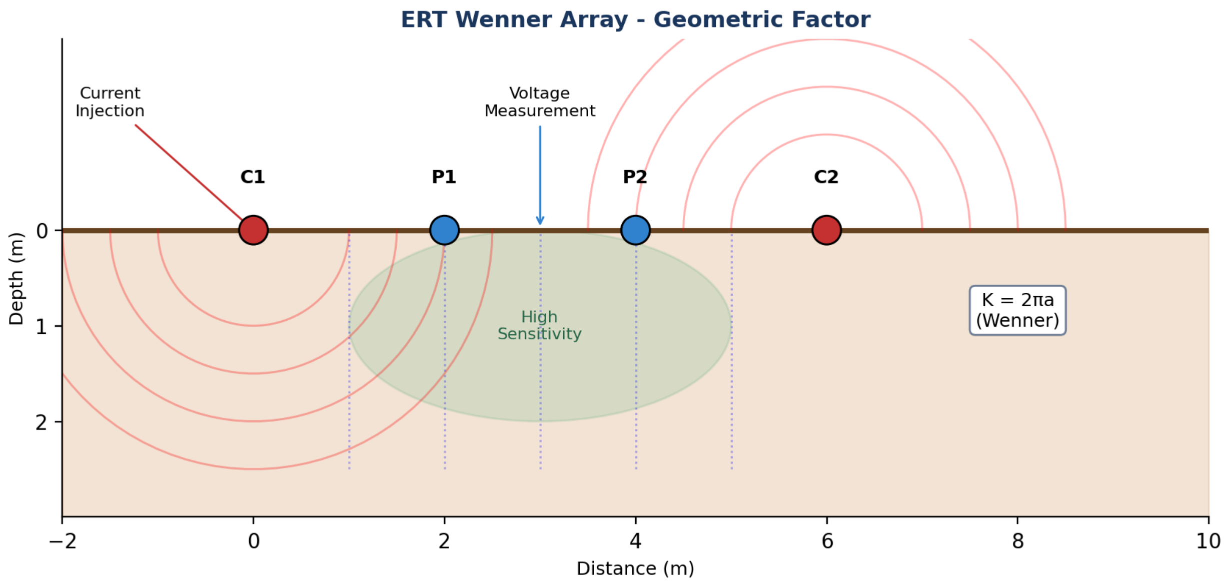

Figure 4. ERT Wenner array configuration showing current injection electrodes (C1, C2) and potential measurement electrodes (P1, P2). Red curves indicate current flow lines; blue dashed lines show equipotential surfaces. The green ellipse marks the zone of maximum sensitivity. The geometric factor K = $2\pi a$ for equal electrode spacing a.

2.5.3 Depth of Investigation

The ERT depth of investigation (DOI) is approximately 1.5x the maximum electrode separation. For HIRT probe configurations:

- **1.5 m probes** (rings at 0.5m, 1.5m): DOI = 2-3 m
- **3.0 m probes** (rings at 0.5m, 1.5m, 2.5m): DOI = 3-5 m (edge cases to 6 m)

2.6 Multi-Frequency Response

Different subsurface features exhibit characteristic frequency-dependent responses that enable target discrimination. Metal targets respond strongly at lower frequencies where skin depth into the metal is greater. Soil disturbances and moisture contrasts show broader, less frequency-dependent signatures.

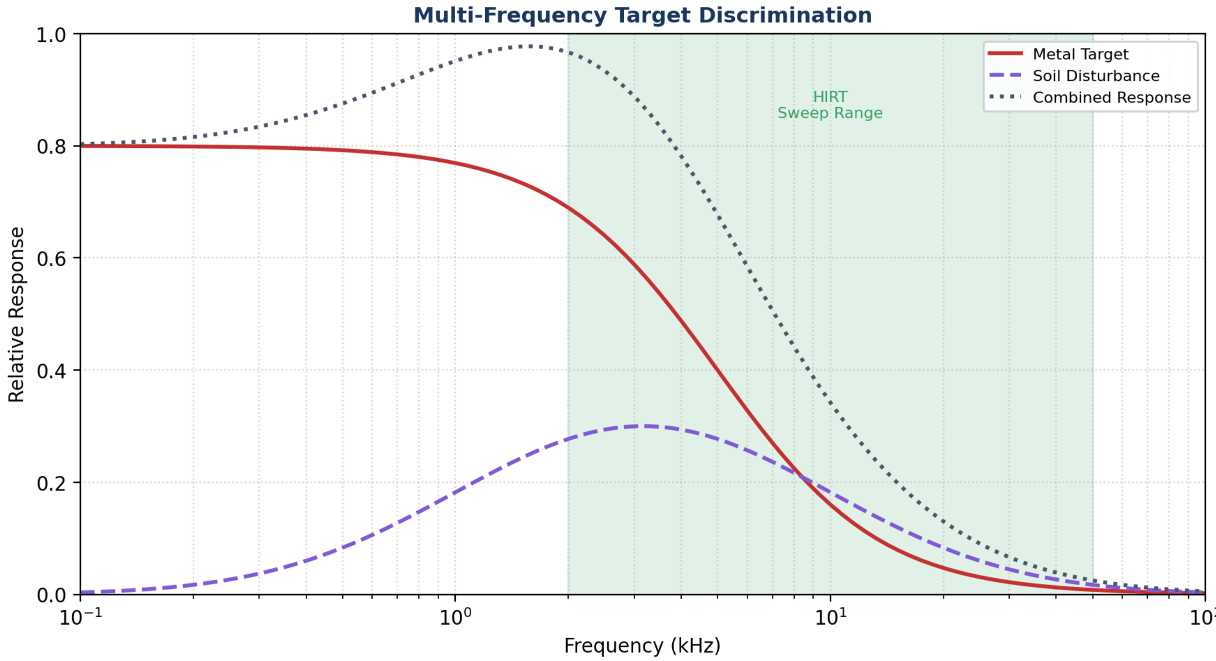

Figure 5. Multi-frequency target discrimination. Metal targets (red) show strong response at lower frequencies with characteristic roll-off. Soil disturbances (purple, dashed) exhibit broader frequency response. The combined signal (gray, dotted) can be decomposed through multi-frequency analysis. The green region indicates the HIRT sweep range (2-50 kHz).

Multi-frequency sweeps enable:

- **Target classification**: Metal vs. soil anomaly discrimination based on spectral signature
- **Depth estimation**: Lower frequencies see deeper; response vs. frequency constrains depth
- **Size estimation**: Larger metal objects have lower characteristic frequencies
- **Conductivity mapping**: Frequency response shape indicates soil conductivity distribution

2.7 Why Crosshole Geometry Beats Surface Methods

HIRT's borehole/crosshole tomography provides fundamental physics advantages over surface geophysical methods for targets deeper than approximately 1.5 m. These advantages stem from the geometry of measurement ray paths.

2.7.1 Ray Path Geometry

Surface methods must send energy down to a target and receive the return signal—doubling the path length and exponentially increasing attenuation. Sensitivity decreases as $1/r^2$ to $1/r^4$ with depth.

Crosshole methods send signals horizontally through the target volume. Energy travels directly between probes at depth, with sensitivity concentrated precisely where targets are located. This geometry provides 2-5x better resolution than surface methods at depths exceeding 2 m.

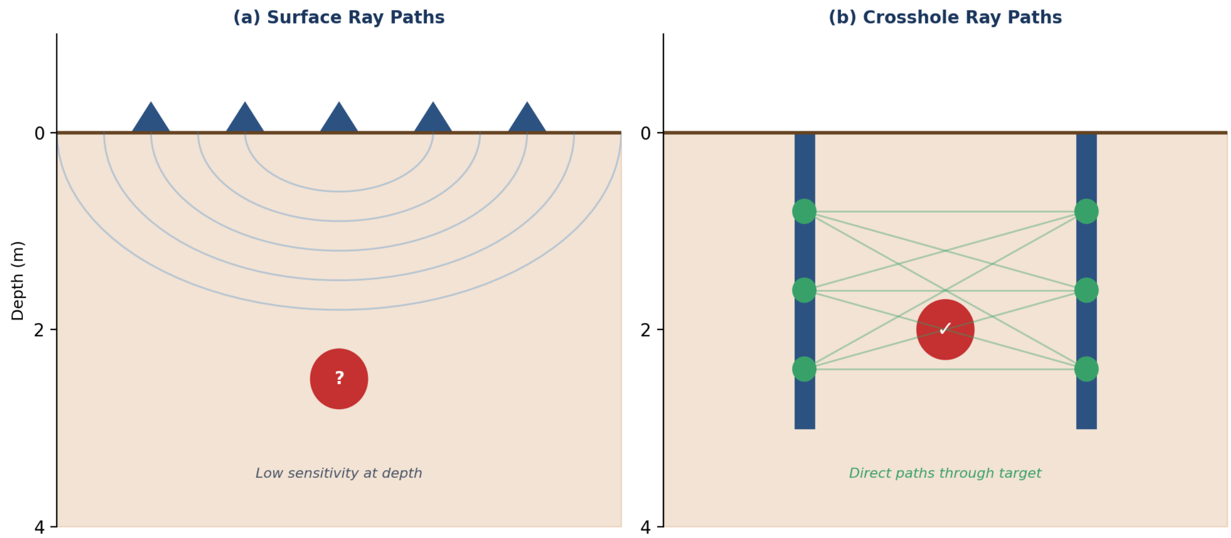

Figure 6. Comparison of (a) surface and (b) crosshole ray path geometries. Surface sensors create curved, indirect paths with poor sensitivity at depth. Crosshole probes provide direct, straight paths through the target volume. The checkmark in (b) indicates confident target detection; the question mark in (a) indicates ambiguous response at depth.

2.7.2 Additional Crosshole Advantages

Beyond ray path geometry, crosshole methods offer several practical advantages:

- **No surface interference**: Measurements occur below near-surface heterogeneity, fill, roots, and cultural noise (fences, vehicles)
- **True 3D sampling**: Multiple ray paths at different angles enable tomographic reconstruction—not pseudo-depth estimation from diffraction patterns
- **Superior depth discrimination**: Targets at 3 m vs. 4 m depth are clearly distinguishable; surface methods show nearly identical responses

Method	Lateral Resolution	Depth Resolution	At 3m Depth
Surface Magnetometry	1-2 m	Poor	~2 m
GPR	0.3-0.5 m (shallow)	0.05-0.1 m (shallow)	>1 m in clay
Surface ERT (Wenner)	~1x spacing	~0.5x spacing	2-3 m
EM31/CMD	1-2 m	Poor	~2 m
HIRT Crosshole	0.5-1x spacing	0.3-0.5x spacing	0.75-1.5 m

Table 4. Resolution comparison across geophysical methods. HIRT crosshole geometry maintains superior resolution at depth where surface methods degrade significantly.

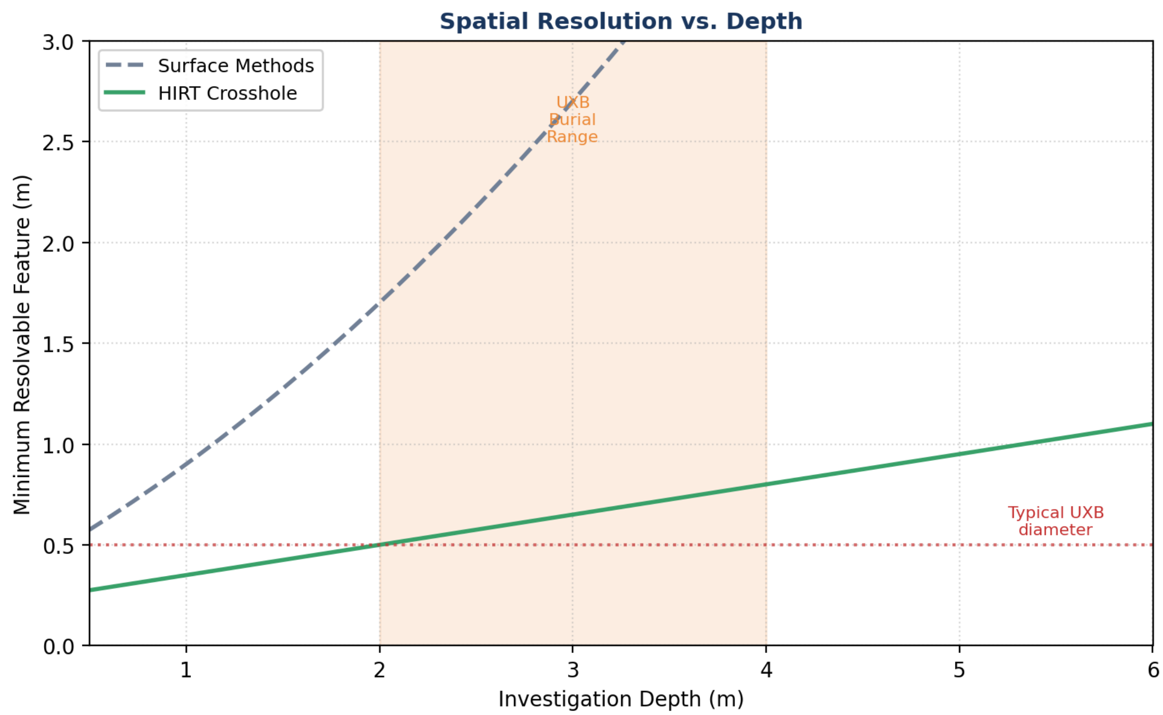

Figure 7. Spatial resolution versus investigation depth. Surface methods (dashed gray) show quadratic degradation of resolution with depth. HIRT crosshole methods (solid green) maintain approximately linear resolution scaling. The red dashed line indicates typical UXB diameter (~0.5 m). The orange shaded region marks typical UXB burial depths (2-4 m).

2.8 Depth of Investigation Summary

The effective investigation depth depends on probe configuration, soil conditions, and the measurement technique (MIT vs. ERT). The following table summarizes depth capabilities with associated confidence levels:

Configuration	MIT Depth	ERT Depth	Combined Claim
1.5 m probes, 2 m spacing	2-3 m	2-3 m	2-3 m (HIGH confidence)
3.0 m probes, 2 m spacing	3-4 m	3-5 m	3-5 m (MEDIUM confidence)
Edge cases (conductive soil)	2-3 m	4-6 m	Up to 6 m (LOW confidence)

Table 5. Depth of investigation summary by configuration and confidence level. Conservative claims are appropriate for field planning; extended depths may be achievable under favorable conditions.

Rule of thumb: With rods inserted to depth D, the sensitivity volume typically extends D to 1.5D below the surface. Actual depth depends on soil conductivity, probe spacing, measurement frequency (MIT), and current injection geometry (ERT).

2.9 When Crosshole Wins vs. Loses

The physics supports strategic use of both surface and crosshole methods. Understanding their respective strengths enables optimal workflow design.

HIRT crosshole geometry is SUPERIOR for:

• Targets deeper than 1.5-2 m

• 3D localization requirements
• Conductive soils where GPR fails
• Distinguishing multiple targets at similar depths
• Non-ferrous (aluminum) target detection

Surface methods remain SUPERIOR for:

• Rapid large-area screening (10x faster coverage)
• Shallow targets (<1 m) where GPR resolution excels
• Purely ferrous targets (magnetometry)
• Initial site characterization before targeted investigation

RECOMMENDED WORKFLOW

- Stage 1: Surface screening (magnetometry, GPR, EM31) to identify anomalies quickly over large areas
- Stage 2: HIRT crosshole follow-up to characterize identified anomalies with superior 3D resolution
- This two-stage approach leverages the strengths of both methods while minimizing deployment time

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Section 3: System Architecture

Micro-Probe Design and Zone Wiring Strategy

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

3.1 Design Philosophy

"Archaeologist brain first, engineer brain second" - This guiding principle shapes every aspect of the HIRT system architecture. The primary goal is to minimize ground disturbance while maintaining sufficient measurement quality for target detection. The result is a probe design with 10-16 mm outer diameter (target: 12-16 mm), representing approximately 10x less ground disturbance than traditional 25+ mm geophysical probes.

The design philosophy embraces a key constraint: many thin, gentle holes are preferable to fewer large ones. This approach is particularly important for sensitive archaeological contexts where visible disturbance must be minimized and backfilling should leave no lasting trace of the survey.

3.2 Probe Overview (Passive Micro-Probes)

Each HIRT probe is fundamentally **passive** - containing no active electronics downhole. Only sensors and wiring reside within the probe body, with all signal conditioning and processing occurring at the central electronics hub. This architecture offers significant advantages in reliability, cost, and field serviceability.

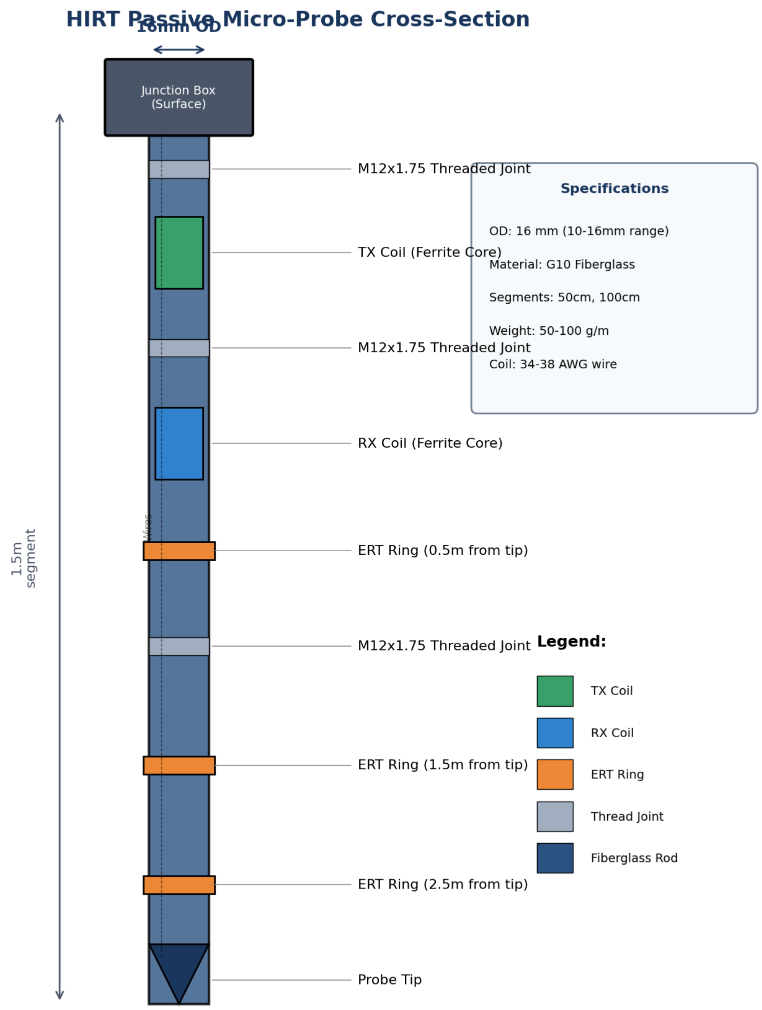

Figure 1. HIRT passive micro-probe cross-section showing internal component arrangement. TX and RX coils are wound on ferrite cores (6-8 mm diameter) and mounted along the fiberglass rod. ERT rings are flush-mounted at standard positions (0.5m, 1.5m, 2.5m from tip). Modular M12x1.75 threaded joints allow field assembly of multiple segments.

MIT Coil Set

- **1x TX coil + 1x RX coil** wound on ferrite cores
- **Ferrite cores:** 6-8 mm diameter x 40-80 mm long
- **Mounting:** Glued along rod (not in bulky head) for streamlined profile
- **Orientation:** Orthogonal or slightly separated to reduce direct coupling
- **Wire:** Fine wire (34-38 AWG), 200-400 turns for adequate signal strength

ERT-Lite Rings

- **2-3 narrow ring electrodes** (3-5 mm wide bands)
- **Standard positions:** 0.5 m and 1.5 m from tip
- **Deep extension:** Add third ring at 2.5-3.0 m for longer rods
- **Material:** Stainless steel or copper foil

- **Mounting:** Bonded with epoxy, flush with rod surface

Rod Construction

- **Material:** Fiberglass (G10) or carbon-fiber segments
- **OD:** 10-16 mm (target: 16 mm with flush joints)
- **Segments:** 50 cm or 100 cm lengths with M12x1.75 threaded couplers
- **Total depth:** Up to 3 m with coupled segments
- **Weight:** ~50-100 g per meter (much lighter than 25mm design)

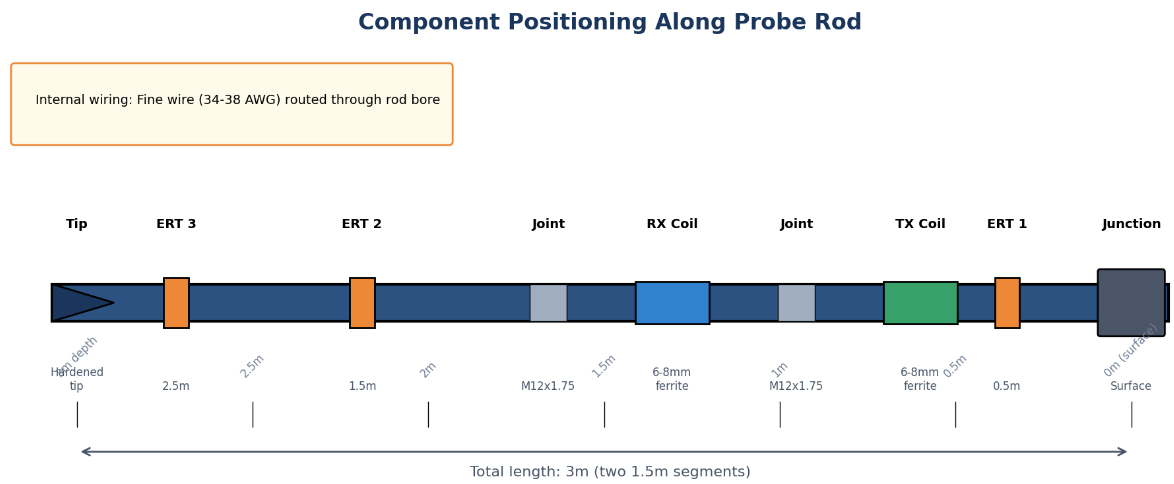

Figure 2. Component positioning along a 3-meter probe assembly. Sensors are distributed to maximize coverage: TX coil near surface for strong drive, RX coil at mid-depth, and ERT rings at three depths for resistivity profiling. Threaded joints allow field disassembly for transport.

3.3 Central Electronics Hub

All active electronics reside in a central hub unit, typically housed in a rugged IP65-rated enclosure. This centralized architecture simplifies probe design, reduces per-probe cost, and enables sophisticated signal processing that would be impractical in distributed electronics.

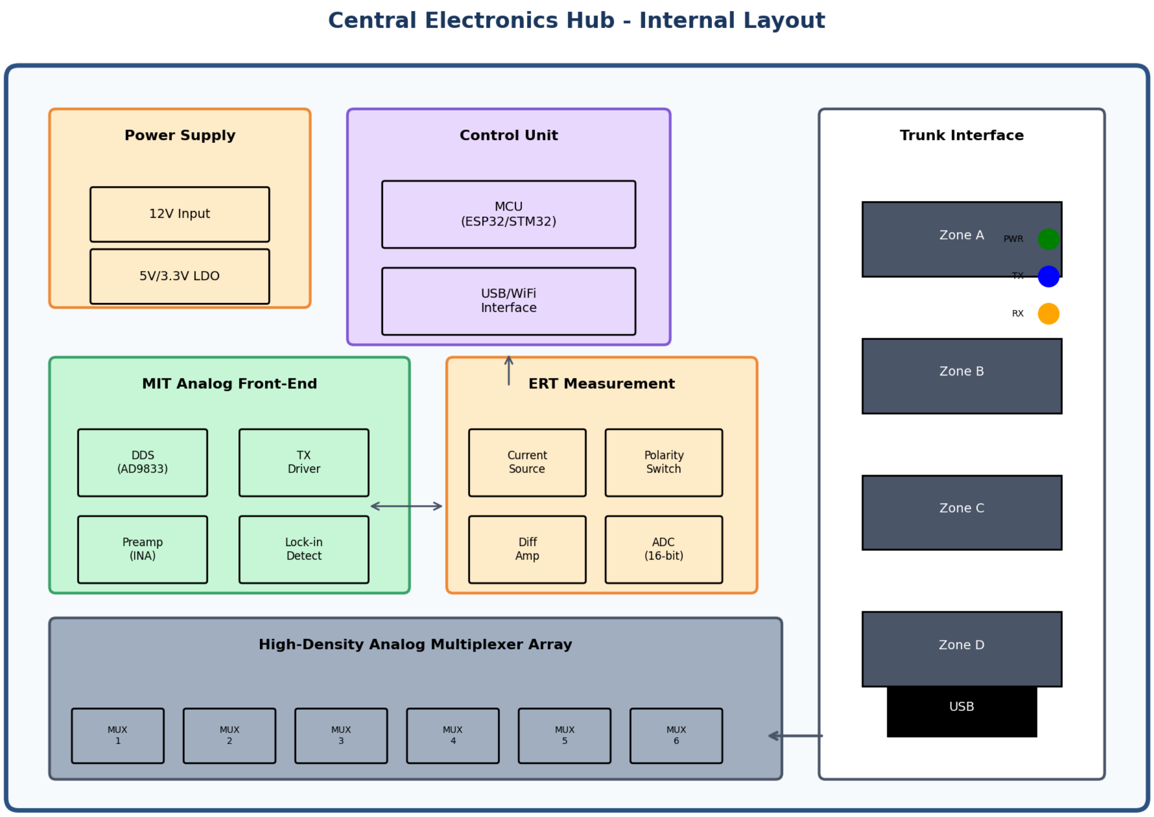

Figure 3. Central Electronics Hub internal layout. The hub contains power supply, MCU (ESP32 or STM32), MIT analog front-end (DDS transmitter and lock-in receiver), ERT current source and measurement circuitry, and the high-density analog multiplexer array. DB25 connectors provide interface to Zone Hub trunk cables.

MIT Driver/Receiver

- **Central DDS sine source** (e.g., AD9833) for 2-50 kHz operation
- **TX driver amplifier** - drives all probe TX coils via trunk cables (10-50 mA)
- **RX low-noise amplifier chain** - instrumentation amplifier with G=1000
- **ADC/lock-in detection** - digital synchronous demodulation
- **MCU** (ESP32 or STM32) for control, DSP, and data acquisition

ERT System

- **Howland current source** - 0.5-2 mA, programmable via DAC
- **Polarity reversal** - H-bridge for DC measurements with polarity cycling
- **Voltage measurement** - differential amplifier (INA128) + 24-bit ADC
- **Multiplexer** - High-density matrix (CD74HC4067) to switch electrode pairs

Power and Communications

- **Power:** 12V or 5V battery pack, 10-20 Ah for full-day field operations
- **Distribution:** Power remains at hub; only signals traverse trunk cables
- **Data logging:** USB or WiFi connection to field tablet

- **Control:** Centralized MCU handles all scheduling and sequencing

3.4 System Block Diagram

The complete HIRT system follows a hierarchical architecture: Central Electronics Hub connects to multiple Zone Hubs via high-density trunk cables, with each Zone Hub serving as a passive breakout for 4 individual probes. This scalable design supports arrays from 4 probes (single zone) to 50+ probes (12+ zones).

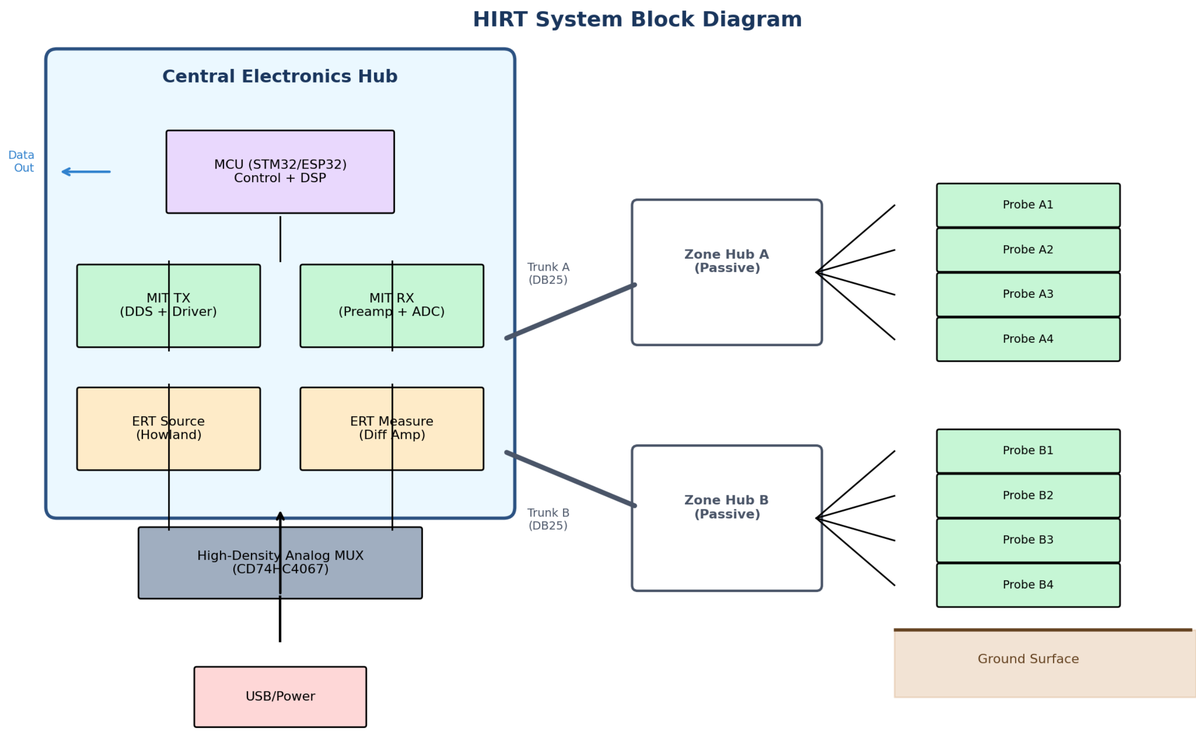

Figure 4. HIRT system block diagram showing the hierarchical architecture. The Central Electronics Hub contains all active circuitry. High-density trunk cables (DB25) connect to passive Zone Hubs, which distribute signals to individual probes. This architecture minimizes cable complexity while maintaining signal integrity over 10-20m cable runs.

3.5 Scalability Architecture: The Zone Strategy

To scale the system from a small prototype (4-8 probes) to a field-ready array (20-50+ probes) without creating an unmanageable cable harness, HIRT employs a **Zone Wiring Strategy**. This approach divides the array into logical zones, each containing 4 probes connected through a local Zone Hub.

The Challenge

A single passive probe requires 8-12 analog conductors (TX coil pair, RX coil pair, 3x ERT rings, Shield, ID). Connecting 25 probes directly to a central hub would require terminating ~250-300 conductors at a single panel, creating severe mechanical congestion and crosstalk risks.

The Solution: Passive Zone Hubs

1. **Probes connect to a local Zone Hub:** A small, passive IP65 box placed on the ground near the probe cluster.
2. **Zone Hubs connect to the Main Unit:** Via a single high-quality, shielded trunk cable (DB25 or 37-pin connector).

3. **Central Hub manages Zones:** The hub switches between trunk lines to address specific probes via the multiplexer array.

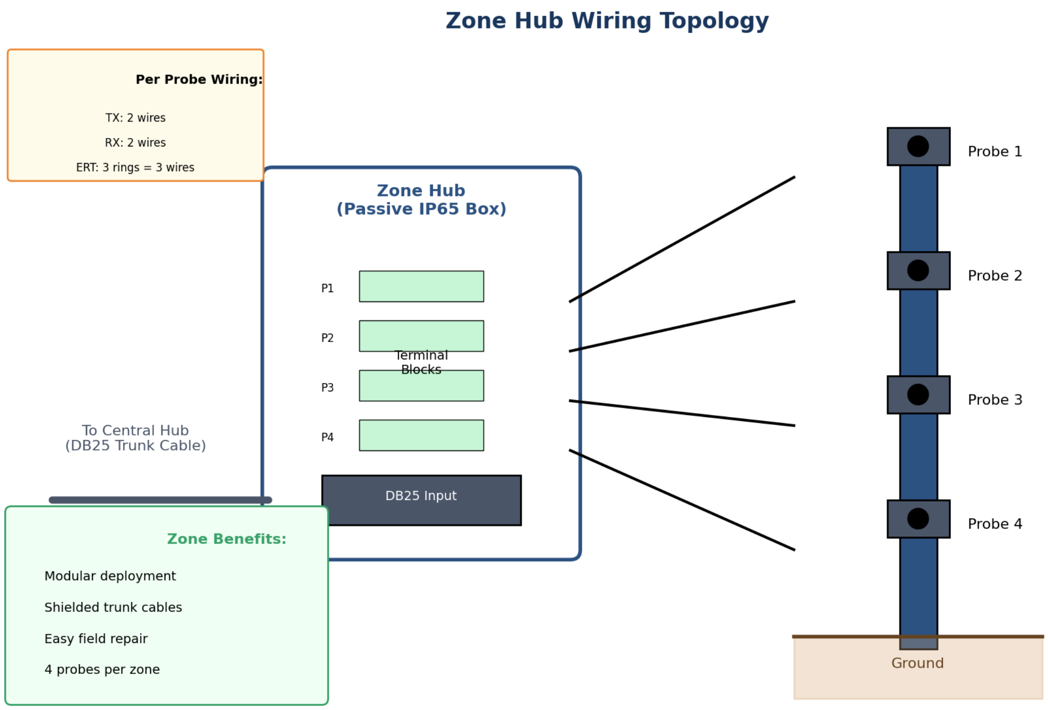

Figure 5. Zone Hub wiring topology. Each passive Zone Hub aggregates connections from 4 probes into a single DB25 trunk cable. Terminal blocks inside the Zone Hub provide strain relief and easy field replacement of individual probe cables. This modular approach dramatically simplifies field deployment.

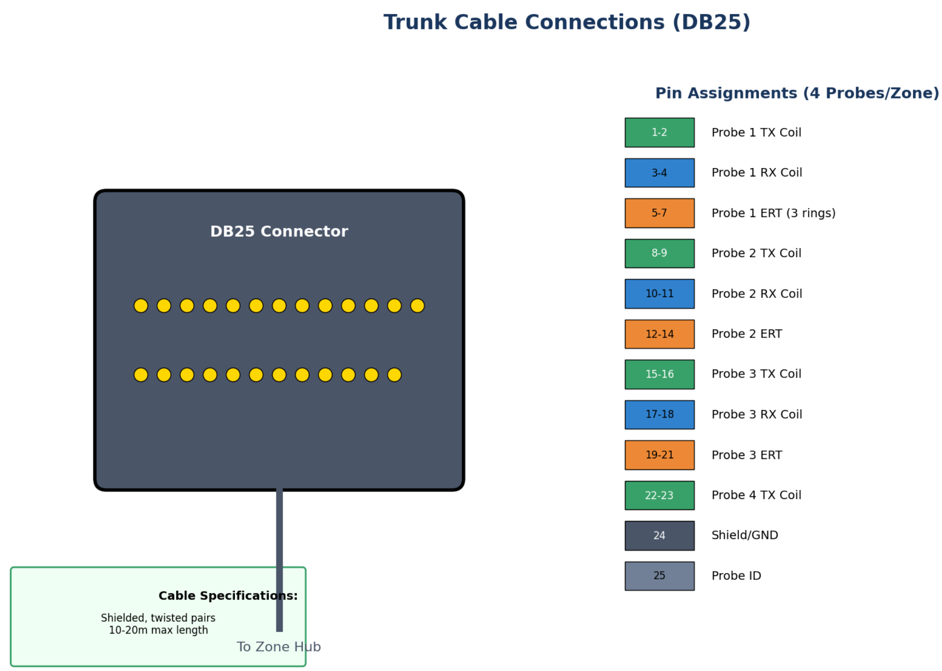

Figure 6. Trunk cable DB25 pin assignments for a 4-probe zone. Each probe uses 7 conductors (TX pair, RX pair, 3 ERT rings), with shared shield and zone ID pins. Shielded twisted-pair cables maintain signal integrity over 10-20m runs from Zone Hub to Central Hub.

ZONE WIRING BENEFITS & NOISE IMMUNITY

- Modular Deployment: Setup involves running a few thick cables rather than dozens of thin ones
- Signal Integrity: Trunk cables utilize individual shielded twisted pairs for all analog lines
- Noise Rejection: Differential signaling (balanced TX drive, instrumentation amp RX) rejects common-mode noise
- Field Repair: A damaged probe cable only affects one local zone, not the main harness
- Scalability: Add zones as needed without redesigning the core system

3.6 Signal Flow Paths

MIT Signal Path

The MIT measurement chain begins with the MCU generating a sine wave via Direct Digital Synthesis (DDS), which is converted to analog, filtered, and amplified to drive the TX coil. The induced signal in the RX coil passes through a high-gain amplifier chain before synchronous demodulation extracts amplitude and phase information.

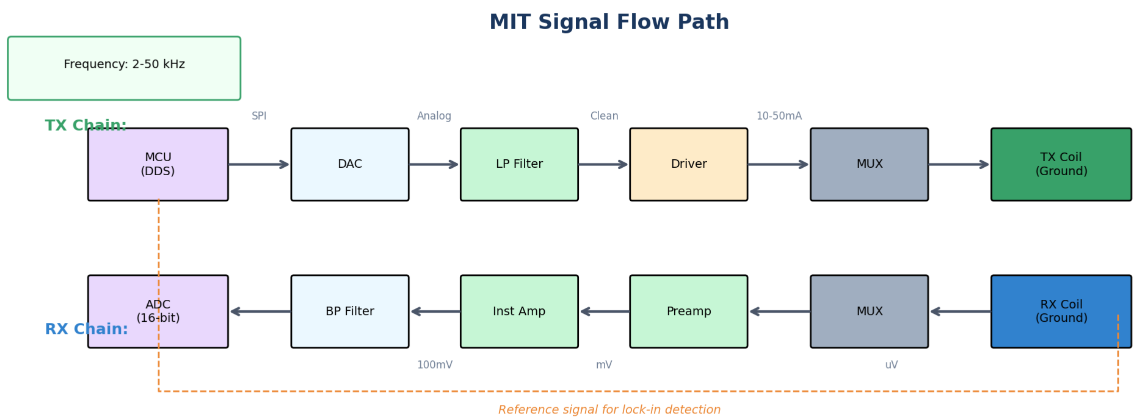

Figure 7. MIT signal flow from DDS generation through TX drive and RX amplification. The lock-in detection uses the reference signal from the DDS to perform synchronous demodulation, extracting both in-phase (resistive) and quadrature (reactive) components. Operating frequency range: 2-50 kHz.

ERT Signal Path

The ERT system injects a known current (0.5-2 mA) between selected electrode pairs and measures the resulting voltage distribution. A Howland current source provides stable current injection regardless of load impedance, while a precision differential amplifier rejects common-mode noise from the measurement electrodes.

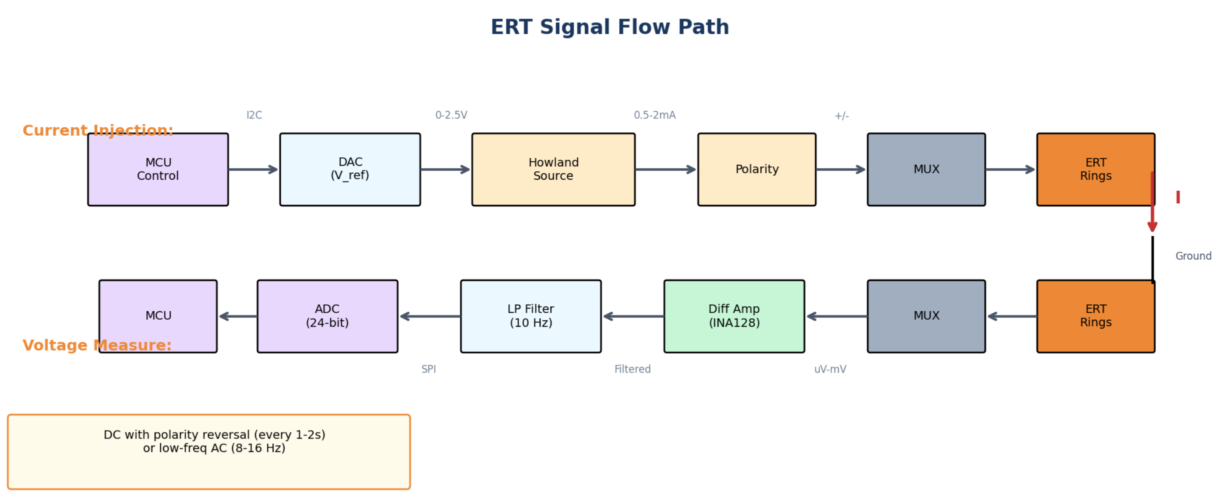

Figure 8. ERT signal flow showing current injection and voltage measurement paths. The Howland current source provides output impedance >1M ohm, ensuring stable injection regardless of electrode contact resistance. Polarity reversal (every 1-2 seconds) cancels electrode polarization effects.

3.7 Multiplexer Switching Topology

The analog multiplexer array is central to HIRT's ability to address any probe in the array. Using CD74HC4067 16:1 analog multiplexers, the system can route TX drive signals to any probe's TX coil and simultaneously route any RX coil to the receiver chain. Similar switching enables flexible ERT electrode pair selection.

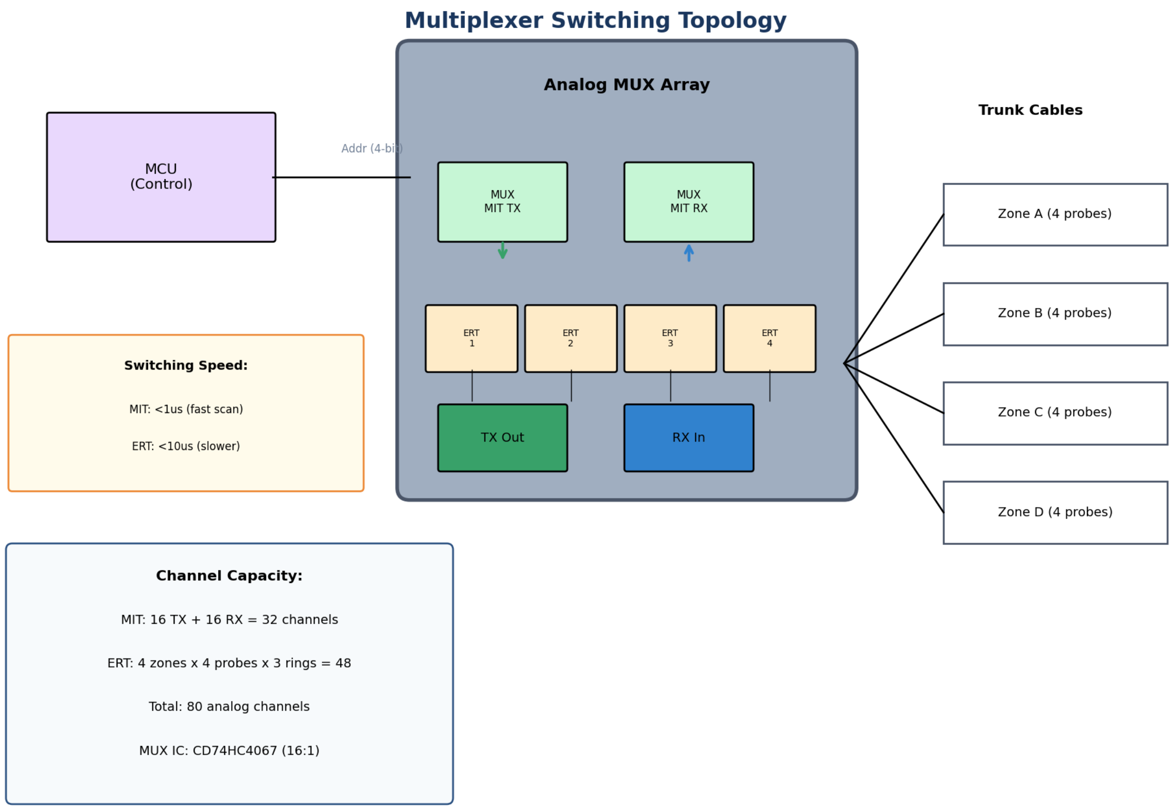

Figure 9. Multiplexer switching topology showing channel allocation across MIT and ERT subsystems. The MCU controls all MUX address lines, enabling any-to-any probe addressing. Total capacity: 80+ analog channels (32 MIT + 48+ ERT) using cascaded 16:1 multiplexers.

3.8 Array Configuration Options

The HIRT system supports multiple array geometries optimized for different investigation scenarios. Array configuration affects both lateral resolution and the distribution of ray paths through the target volume. The following standard configurations address common field requirements.

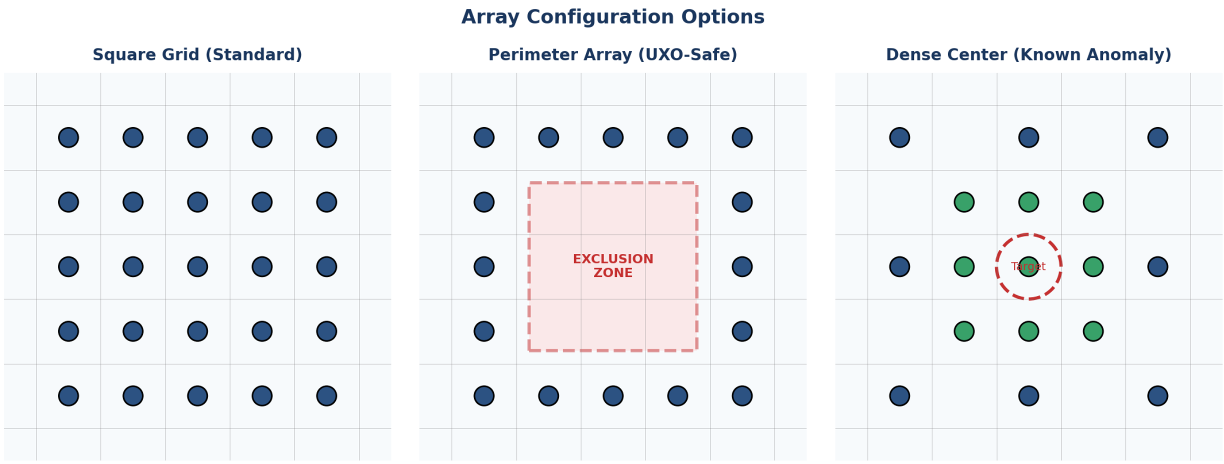

Figure 10. Standard array configuration options. (a) Square grid provides uniform coverage for unknown target locations. (b) Perimeter array enables safe standoff from suspected UXO while maintaining imaging capability. (c) Dense center configuration concentrates probes around a known anomaly for maximum resolution.

Configuration	Best For	Probe Count	Spacing
Square Grid	Unknown target locations	16-36 (4x4 to 6x6)	1.5-2.0 m
Perimeter	UXO/hazard standoff	12-16	1.5-2.0 m
Dense Center	Known anomaly detail	17-25	0.75-1.0 m center

Table 1. Array configuration selection guide.

3.9 Insertion Methods

The slim 16mm probe profile enables multiple insertion methods depending on soil conditions. All methods prioritize minimal disturbance and safe operation.

1. **Hand Auger:** 18-20 mm hand auger creates clearance hole, probe inserted without force
2. **Pilot Rod:** 8-10 mm steel rod driven to depth, wiggled to ~14 mm, removed before probe insertion
3. **Direct Push:** In sandy loam, probe may push directly (requires hardened tip)
4. **Water-Jet:** In sand, water lance fluidizes soil; probe inserted as water drains

INSERTION SAFETY - UXO SITES

- Never hammer or drive probes directly - use pilot hole methods only
- Professional EOD clearance required before any insertion operations
- Maintain 100m exclusion zone during pilot rod operations
- Use perimeter-only deployment when UXB suspected at center

3.10 Advantages of Micro-Probe Design

1. **Minimal Intrusion:** ~10x less ground disturbance than 25mm designs

2. **Easy Insertion:** Lightweight probes (~100g/m) require minimal force
3. **Better Contact:** Slurry/water in insertion hole improves ERT electrode contact
4. **Flexible Deployment:** Can achieve denser spacing; easy removal and backfill
5. **Simplified Electronics:** Centralized hub is easier to maintain; passive probes are more reliable
6. **Archaeology-Friendly:** Acceptable for sensitive contexts with minimal visual impact

3.11 Software Pipeline Roadmap

While this document focuses on hardware, the HIRT system is designed to output data compatible with established open-source inversion frameworks. The 'Stage 2' software pipeline is currently in development to leverage these powerful tools:

- **EIDORS (Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software):** Primary target for MIT-3D image reconstruction using finite element models.
- **pyGIMLi (Geophysical Inversion and Modeling Library):** Target framework for coupled ERT/MIT inversion and multi-physics mesh generation.
- **ResIPy:** User-friendly interface for the ERT component processing and inversion.

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Section 4: Bill of Materials

Complete Parts List for HIRT System Construction

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

4.1 Overview

This section provides comprehensive bills of materials (BOMs) for building the HIRT system, including per-probe components, base hub components, and shared equipment. The micro-probe design (16mm OD, passive probes) minimizes cost while maintaining measurement quality.

The modular architecture allows builders to scale the system from a minimal single-probe test setup to full 25+ probe arrays. Component selection prioritizes availability, cost-effectiveness, and ease of assembly while meeting performance specifications.

4.2 Cost Summary

System Cost Estimate (25-Probe Array)

The following table presents the estimated cost ranges for a complete 25-probe HIRT system. Actual costs may vary based on sourcing, quantity discounts, and regional availability.

Category	Cost Range	Notes
Probes (24 units)	$1,400-2,400	Passive design
Central Hub	$200-300	Electronics + Enclosure
Zone Wiring	$150-300	Hubs + Trunk Cables
Tools/Equipment	$100-200	Assembly tools
Consumables	$50-100	Epoxy, solder, etc.
Total	$1,800-3,900	95%+ Savings

Table 1. 24-Probe HIRT System Cost Estimate

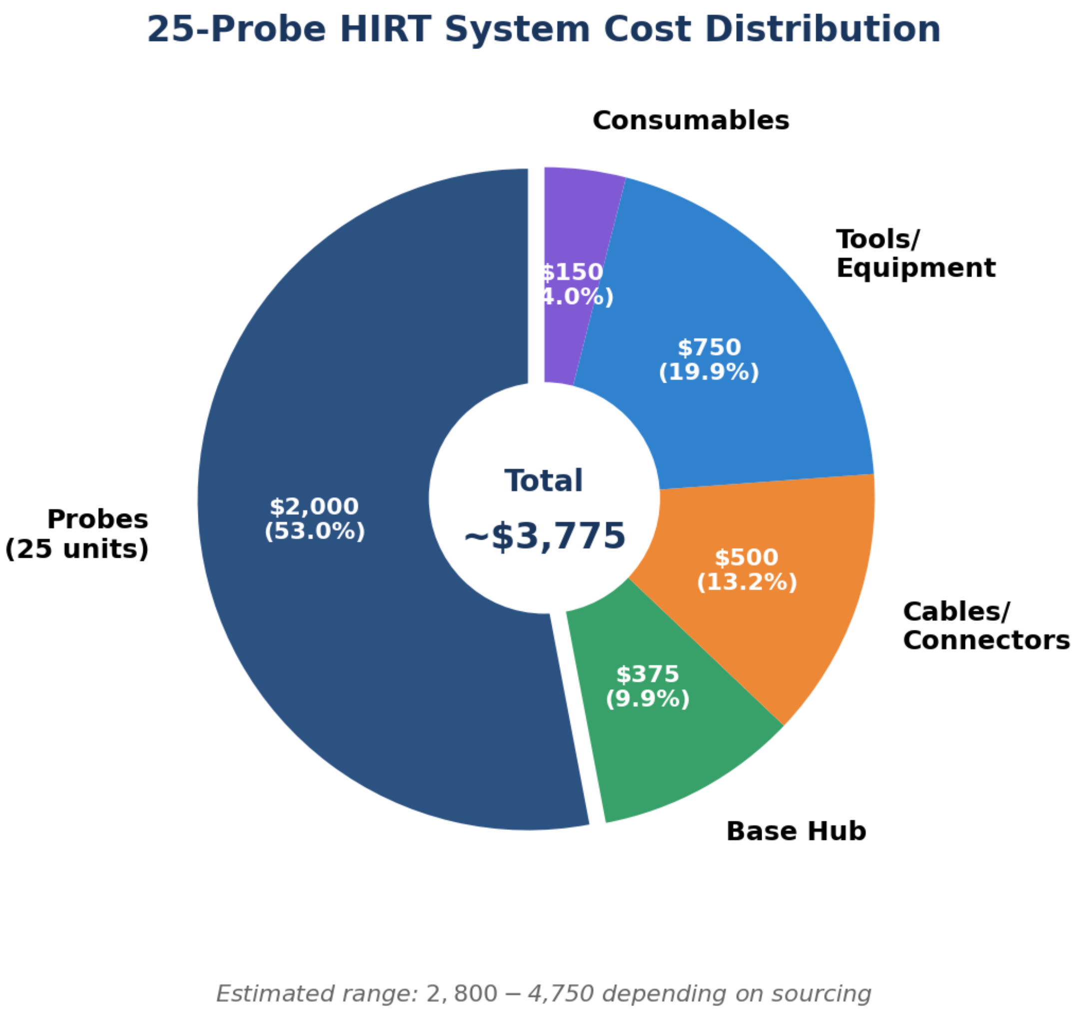


Figure 1. Cost distribution for a 25-probe HIRT system showing the relative investment in each component category. Probes represent the largest expense due to quantity.

Cost Per Probe Breakdown

Each passive probe consists of mechanical, sensing, and interconnection components. The following breakdown shows typical costs for a single probe unit.

Component	Cost
Mechanical (rod, tip, coupler)	$35-55
ERT (rings, collars)	$5-10
Coils (ferrite, wire)	$10-15
Short Cable (1m)	$10-15
Hardware (epoxy, o-rings)	$5-10
Total per probe	$70-120

Table 2. Per-Probe Cost Breakdown (Passive Design)

Cost Reduction Options

- **Bulk ordering:** 20%+ savings on quantities >50 units
- **Local sourcing:** Reduce shipping costs for common components
- **Simpler design:** Passive probes vs active for significant savings
- **DIY coils:** Wind your own coils vs purchasing pre-wound
- **Generic parts:** Use non-branded components where precision is not critical

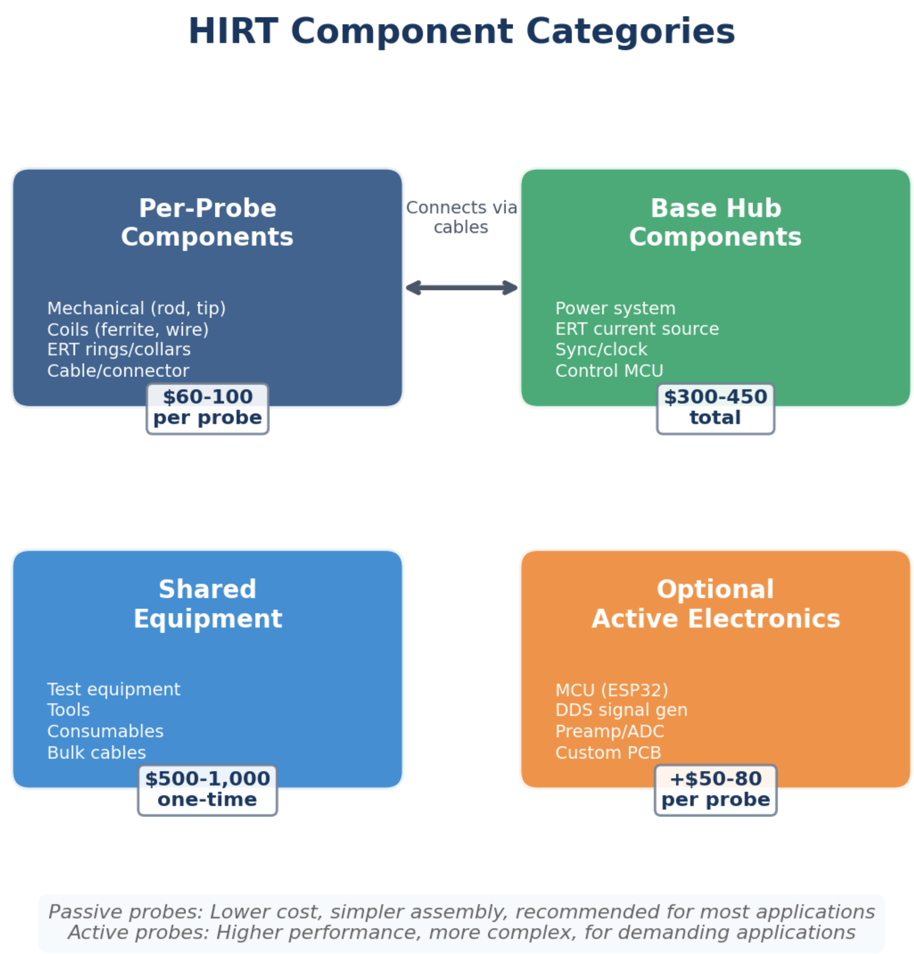


Figure 2. HIRT component categories showing the relationship between per-probe components, base hub electronics, shared equipment, and optional active probe upgrades.

4.3 Per-Probe Bill of Materials

Mechanical Components

Ref	Component	Description	Qty	Unit Cost
ROD1	Fiberglass Tube	16mm OD x 12mm ID x 1.5m	2	$15-25 ea
TIP1	Probe Tip	3D printed PETG	1	$1-2
CPL1	Rod Coupler	3D printed/CNC	1	$2-5
JB1	Junction Box	3D printed PETG	1	$3-5

Table 3. Per-Probe Mechanical Components

Coil Components

Ref	Component	Description	Qty	Unit Cost
L1	Ferrite Rod	6-8mm x 40-80mm MnZn	1-2	$2-5
W1	Magnet Wire	34-38 AWG, 50m	1	$3-5

Table 4. Per-Probe Coil Components

ERT Components

Ref	Component	Description	Qty	Unit Cost
R1-R3	ERT Rings	Stainless steel 3-5mm bands	2-3	$1-2 ea
C1-C3	Ring Collars	3D printed PETG	2-3	$0.50 ea

Table 5. Per-Probe ERT Components

Hardware

Ref	Component	Description	Qty	Unit Cost
HW1	O-Rings	M12 size, nitrile	4	$0.50 ea
HW2	Epoxy	2-part structural	-	$5/probe

Table 6. Per-Probe Hardware

Cable and Connectors

Ref	Component	Description	Qty	Unit Cost
CBL1	Shielded Cable	6-conductor, 3-5m	1	$10-15
CON1	Connector	12-pin Phoenix	1	$5-8

Table 7. Per-Probe Cable and Connectors

Total Per Passive Probe

- Estimated cost: ~$60-100 per passive probe
- Assembly time: 2-4 hours per probe
- Required skills: Basic soldering, 3D printing, mechanical assembly

Active Probe Electronics (Optional)

For applications requiring higher performance, active probes with in-probe electronics can be built. These include signal generation, amplification, and digitization circuitry.

Ref	Component	Part Number	Qty	Unit Cost
U1	MCU	ESP32-WROOM-32	1	$5-8
U2	DDS	AD9833BRMZ	1	$8-12
U3	TX Op-Amp	OPA454AIDDAR	1	$6-10
U4	RX Preamp	AD620ARZ	1	$6-10
U5	Inst Amp	INA128PAG4	1	$6-10
U6	ADC	ADS1256IDBR	1	$10-15
U7	Mux	CD4051BE	1	$1-2
U8	LDO	AMS1117-3.3	1	$0.50
PCB	Custom PCB	-	1	$5-10
-	Passives	Resistors, caps	-	$5

Table 8. Active Probe Electronics (Optional Add-on)

Additional cost per active probe: ~$50-80. Active probes provide improved signal-to-noise ratio and reduced cable effects but require more complex assembly.

4.4 Base Hub Bill of Materials

The base hub provides power distribution, synchronization, and data collection for all connected probes. One hub supports up to 25 probes.

Power System

Ref	Component	Part Number	Qty	Unit Cost
BAT1	Battery	12V 12Ah LiFePO4	1	$60-100
F1	Fuse Holder	0287005.PXCN	1	$3
F2	Fuse	5A fast-blow	5	$1 ea
REG1	5V Regulator	LM2596 Module	1	$3-5
REG2	3.3V Regulator	AMS1117-3.3	1	$0.50
SW1	Power Switch	DPST 10A	1	$3-5
TB1	Terminal Block	Multi-position	1	$10-15

Table 9. Base Hub Power System Components

ERT Current Source

Ref	Component	Part Number	Qty	Unit Cost
U1	Voltage Ref	REF5025AIDGKR	1	$4-6
U2	Op-Amp	OPA277PAG4	1	$4-6
U3	Inst Amp	INA128PAG4	1	$6-10
K1	Relay	G5V-2-H1	1	$3-5
R1-R4	Precision R	0.1% various	10	$0.50 ea
R5	Sense R	10 ohm 0.1%	1	$1

Table 10. ERT Current Source Components

Sync/Clock Distribution

Ref	Component	Part Number	Qty	Unit Cost
Y1	Oscillator	ECS-100-10-30B-TR	1	$3-5
U1-U3	Buffer	SN74HC244N	3	$1 ea

Table 11. Sync/Clock Distribution Components

Communication

Ref	Component	Part Number	Qty	Unit Cost
U1	RS485	MAX485ESA+	1	$2-4
U2	USB-Serial	CP2102 Module	1	$3-5
J1	RJ45 Jack	-	1	$2

Table 12. Communication Interface Components

Control

Ref	Component	Part Number	Qty	Unit Cost
U1	MCU	ESP32 DevKit	1	$8-12
U2	ADC	ADS1256IDBR	1	$10-15
SD1	SD Card	Micro SD module	1	$3-5

Table 13. Control System Components

Enclosure and Connectors

Ref	Component	Description	Qty	Unit Cost
ENC1	Enclosure	IP65 200x150x100mm	1	$30-50
PG1-PG20	Cable Glands	PG11 or M20	20	$1 ea
CON1-CON20	Probe Connectors	12-pin Phoenix	20	$5 ea

Table 14. Enclosure and Connector Components

Total Base Hub Cost

- Estimated cost: ~$300-450 for complete base hub
- Assembly time: 8-12 hours
- Testing and calibration: Additional 4-6 hours

4.5 Shared Equipment Bill of Materials

Connectors and Cables

Ref	Component	Description	Qty	Unit Cost
CBL1	Probe Cable	Belden 3066A 12-pair, 5m	20	$15 ea
CBL2	Power Cable	14 AWG 2-conductor	10m	$10
CON1	Phoenix Headers	12-pos pluggable	20	$5 ea
CON2	DC Jack	5.5x2.1mm panel	1	$2

Table 15. Shared Cables and Connectors

Test Equipment (Recommended)

Item	Description	Est. Cost	Notes
DMM	Digital Multimeter	$50-100	Fluke or equivalent
LCR	LCR Meter	$100-300	For coil testing
Scope	Oscilloscope	$300-500	2-ch, 50MHz min
PS	Bench Power Supply	$50-100	Adjustable, current limit

Table 16. Recommended Test Equipment

Tools

Item	Description	Est. Cost
Soldering	Iron + solder	$50-100
Tap/Die	M12x1.75 set	$30-50
Crimpers	For connectors	$30-50
Heat Gun	For shrink tubing	$30-50
Hand Tools	Screwdrivers, pliers	$50

Table 17. Required Tools

Consumables

Item	Description	Est. Cost
Solder	60/40 or lead-free	$15
Flux	Rosin flux	$10
Heat Shrink	Assorted sizes	$15
Epoxy	2-part structural	$20
Cable Ties	Assorted	$10
IPA	Isopropyl alcohol	$10

Table 18. Consumables

4.6 Procurement Guide

Recommended Suppliers

Electronics

- **DigiKey** (www.digikey.com) - Wide selection, fast shipping
- **Mouser** (www.mouser.com) - Good for precision components
- **Newark** (www.newark.com) - Alternative source

Mechanical

- **McMaster-Carr** (www.mcmaster.com) - Hardware, tubing
- **Grainger** (www.grainger.com) - Industrial supplies
- **Amazon** - General supplies

3D Printing

- Local print shop
- **Shapeways** (www.shapeways.com) - Online service
- **JLCPCB** (www.jlcpcb.com) - Also offers 3D printing

PCB Fabrication

- **JLCPCB** (www.jlcpcb.com) - Low cost, fast
- **PCBWay** (www.pcbway.com) - Good quality
- **OSH Park** (oshpark.com) - US-based, quality

Key Part Numbers Reference

Component	DigiKey PN	Mouser PN
AD9833BRMZ	AD9833BRMZ-REEL	584-AD9833BRMZ
AD620ARZ	AD620ARZ-ND	584-AD620ARZ
INA128PAG4	INA128PAG4-ND	595-INA128PAG4
ADS1256IDBR	ADS1256IDBR-ND	595-ADS1256IDBR
OPA454AIDDAR	OPA454AIDDAR-ND	595-OPA454AIDDAR
REF5025AIDGKR	REF5025AIDGKR-ND	595-REF5025AIDGKR
ESP32-WROOM-32	1904-1009-1-ND	356-ESP32-WROOM-32

Table 19. Key Part Numbers for Major Suppliers

Procurement Tips

1. **Order extras:** Add 10-20% for spares and mistakes
2. **Check MOQ:** Some parts have minimum order quantities
3. **Lead times:** Check availability before ordering
4. **Substitutes:** Have backup part numbers identified
5. **Consolidate:** Combine orders to reduce shipping costs

4.7 Alternative Components

The following tables provide alternative component options for situations where primary components are unavailable or when different performance characteristics are desired.

Coil Alternatives

Original	Alternative	Notes
6-8mm ferrite rod	10mm rod	Larger = more signal, larger diameter
30 AWG magnet wire	28-34 AWG	Trade-off: turns vs resistance

Table 20. Coil Component Alternatives

ERT Ring Alternatives

Original	Alternative	Notes
Stainless steel band	Copper tape	Lower cost, easier to work with
3D printed collar	Heat shrink tube	Simpler mounting

Table 21. ERT Ring Alternatives

Electronics Alternatives

Original	Alternative	Notes
AD9833 DDS	Si5351	More outputs, different interface
AD620 preamp	INA217	Different specifications
ADS1256 ADC	ADS1115	Lower resolution, lower cost

Table 22. Electronics Alternatives

For assembly procedures, see Section 7: Assembly and Wiring. For mechanical specifications, see Section 5: Mechanical Design. For electronics schematics, see Section 6: Electronics and Circuits.

Section 5: Mechanical Design

Probe Construction, Threading, Coil Mounting, and Materials

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

5.1 Overview

This section consolidates all mechanical design specifications for the HIRT probe system, including the micro-probe architecture, rod specifications, component drawings, and manufacturing procedures for 3D printed parts. The design philosophy prioritizes minimal ground disturbance while maintaining robust measurement capability.

5.2 Design Philosophy

"Archaeologist brain first, engineer brain second" - This guiding principle shapes every aspect of the HIRT mechanical design. The goal is to create the smallest possible hole while retaining enough physics (coil area, electrode contact) for quality signals. The constraint leads to many thin, gentle holes rather than few large ones, resulting in approximately 10x less disturbance than conventional designs.

5.2.1 Core Design Principles

- **No big electronics at the tip:** PCBs, ADCs, MCUs stay at surface. Only passive components downhole.
- **Probes are mostly passive:** Downhole contains only coils and electrodes plus thin wiring. All 'smart' electronics reside in junction box above ground.
- **Rod diameter standard: 16mm OD:** Robust hiking pole standard allowing strong M12 threads. Hole size of 18-20mm is much less destructive than traditional 50mm.

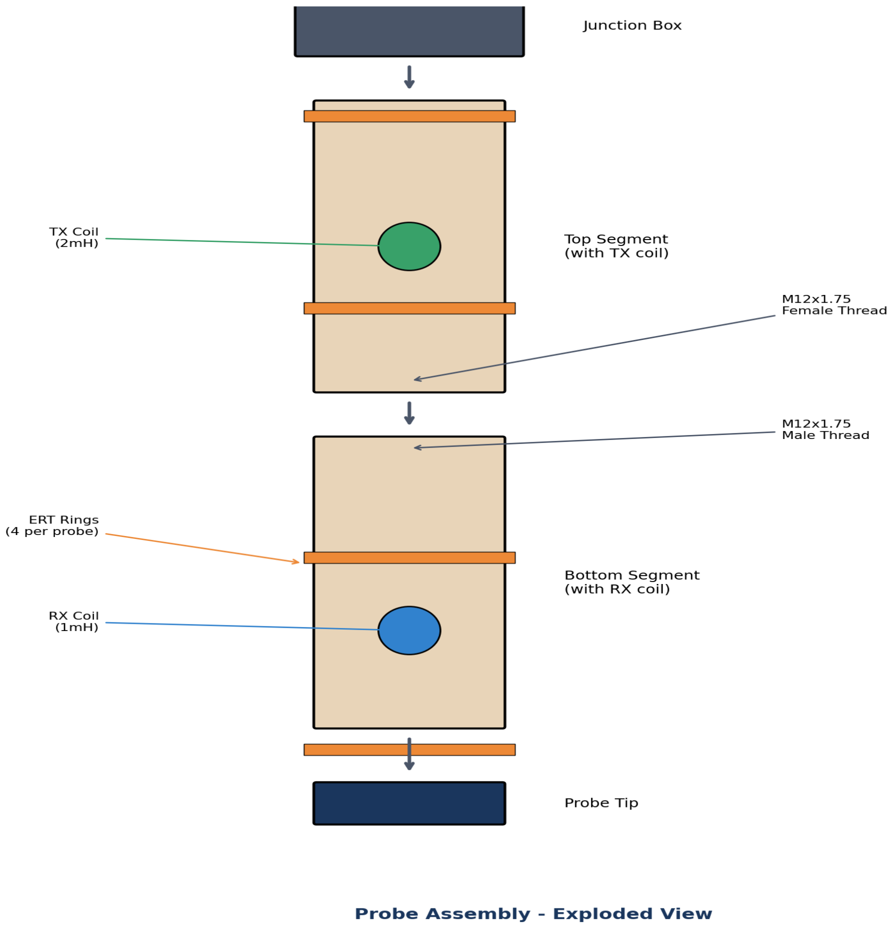


Figure 1. Probe assembly exploded view showing the modular construction with M12x1.75 threaded connections. Components from bottom: probe tip, rod segments with integrated coils, ERT ring collars, and surface junction box. All parts screw together for field assembly.

5.2.2 Disturbance Comparison

The micro-probe design achieves dramatic reduction in soil disturbance compared to traditional geophysical probes. A 16mm rod requires only an 18-20mm hole, with cross-sectional area of approximately 2.5-3.0 cm^2. At 3m depth, this creates only 0.75-1.0 liters of displacement per hole. In contrast, traditional 25mm rods requiring 50mm holes displace approximately 6 liters per hole - a 7-10x increase in disturbance.

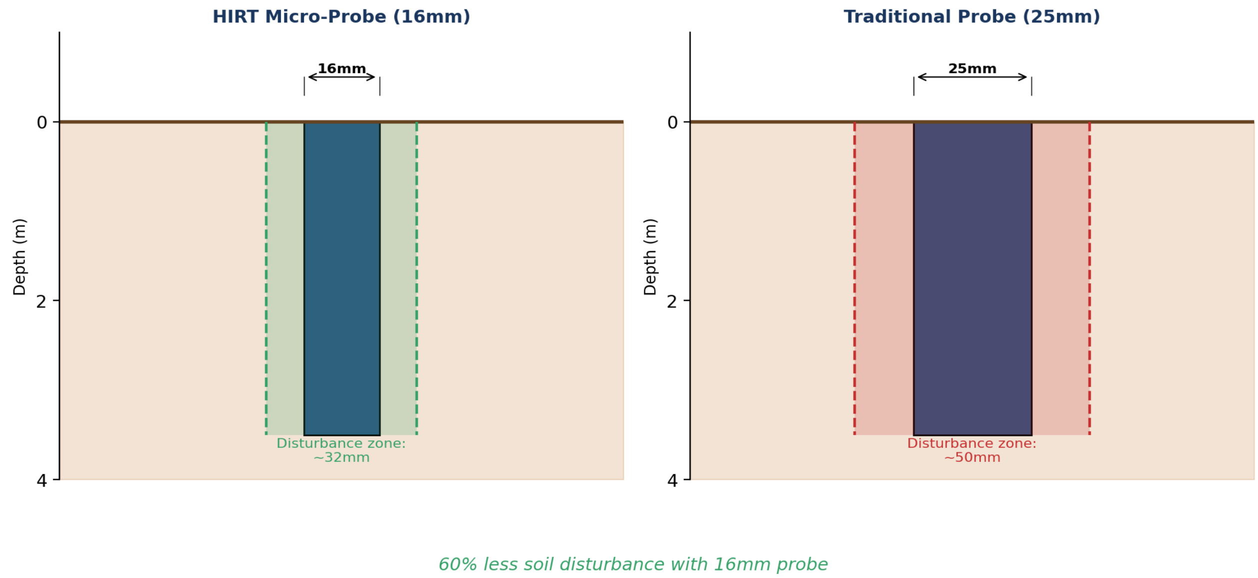


Figure 2. Soil disturbance comparison between HIRT micro-probe (16mm) and traditional probe (25mm). The dashed lines indicate the disturbed zone extent. The 16mm design achieves approximately 60% less soil disturbance, critical for archaeological site preservation.

5.3 Key Dimensions

Component	Dimension	Notes
Rod OD	16 mm	Increased from 12mm for strength
Rod ID	12-13 mm	Standard pultruded tube
Wall Thickness	1.5-2.0 mm	Structural requirement
Segment Length	50, 100 cm	Defines sensor spacing
Hole Size	18-20 mm	For 16mm rod insertion
Total Length	2.5-3.0 m	Multiple segments assembled

Table 1. Key dimensional specifications for the HIRT micro-probe system.

5.4 Rod Segments and Couplers

5.4.1 Rod Material Selection

Material selection is critical for probe performance. The rod must be non-conductive to avoid interference with electromagnetic measurements, strong enough to withstand insertion forces, and durable for repeated field use. Fiberglass (G10) emerges as the preferred material due to its combination of high strength, non-conductivity, RF transparency, and moderate cost.

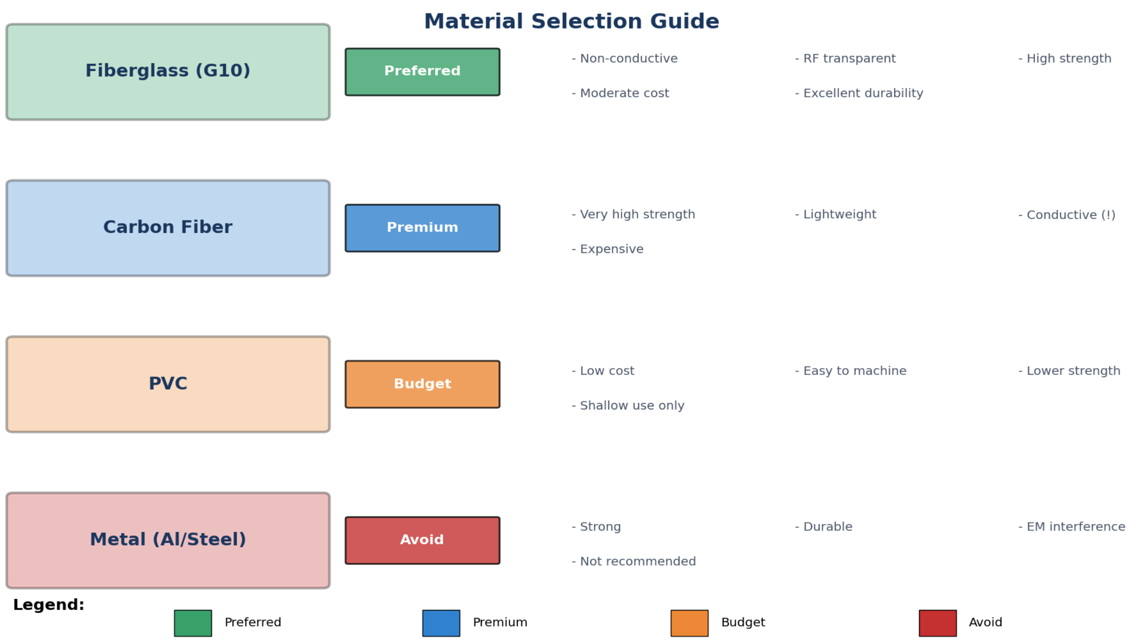


Figure 3. Material selection guide for probe rod construction. Fiberglass (G10) is the preferred material offering the best balance of strength, non-conductivity, and cost. Metal rods must be avoided as they interfere with electromagnetic measurements.

Parameter	Specification
Outer Diameter (OD)	16 mm (approx. 5/8")
Inner Diameter (ID)	12-13 mm
Wall Thickness	~1.5-2.0 mm
Material	Fiberglass (non-conductive, RF transparent)
Segment Lengths	50 cm, 100 cm (spacers)

Table 2. Fiberglass rod specifications.

5.4.2 Modular Connector System

The system uses a 2-part connector system permanently epoxied into rod ends to create a screw-together stack. The male insert provides the threaded portion while the female insert/sensor module receives the thread and houses sensors. This flush-mount design ensures a smooth 16mm OD profile throughout, preventing snag points during insertion and extraction.

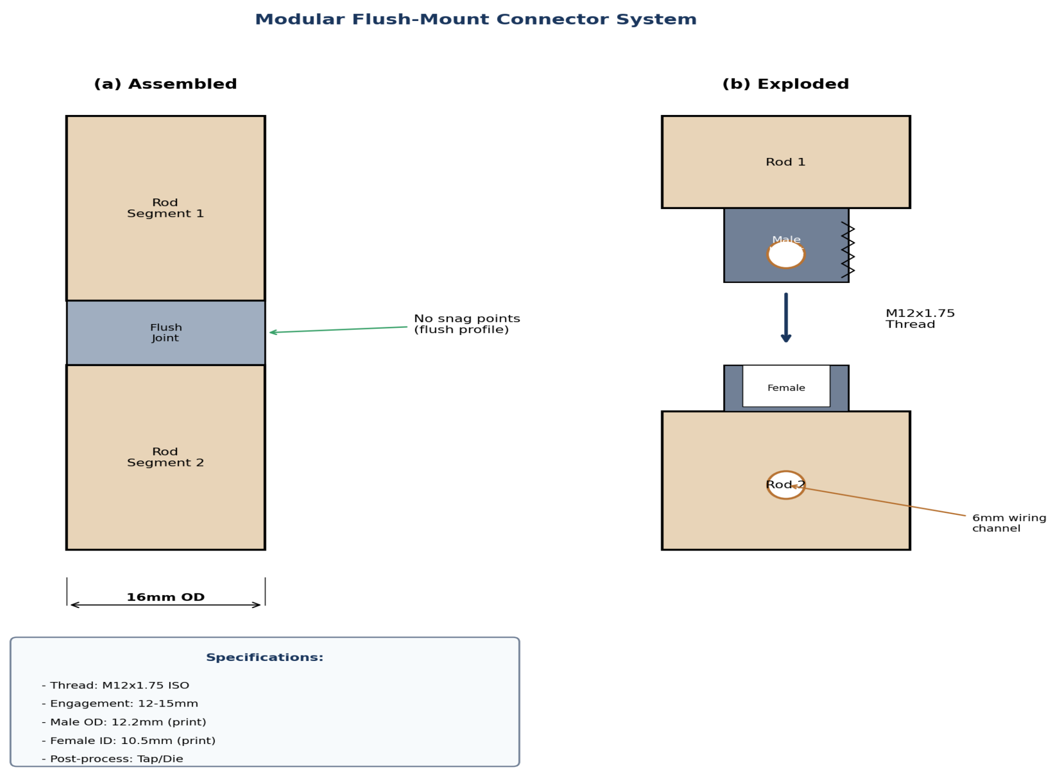


Figure 4. Modular flush-mount connector system showing (a) assembled view with smooth profile and (b) exploded view revealing male/female insert architecture. The 6mm central channel accommodates wiring. M12x1.75 threads provide robust mechanical connection.

5.4.3 Thread Specifications

All threaded connections use M12x1.75 ISO standard metric threads. This provides adequate strength for field assembly while remaining manufacturable via 3D printing with post-processing. The 'chunky' thread profile improves printability while maintaining engagement strength.

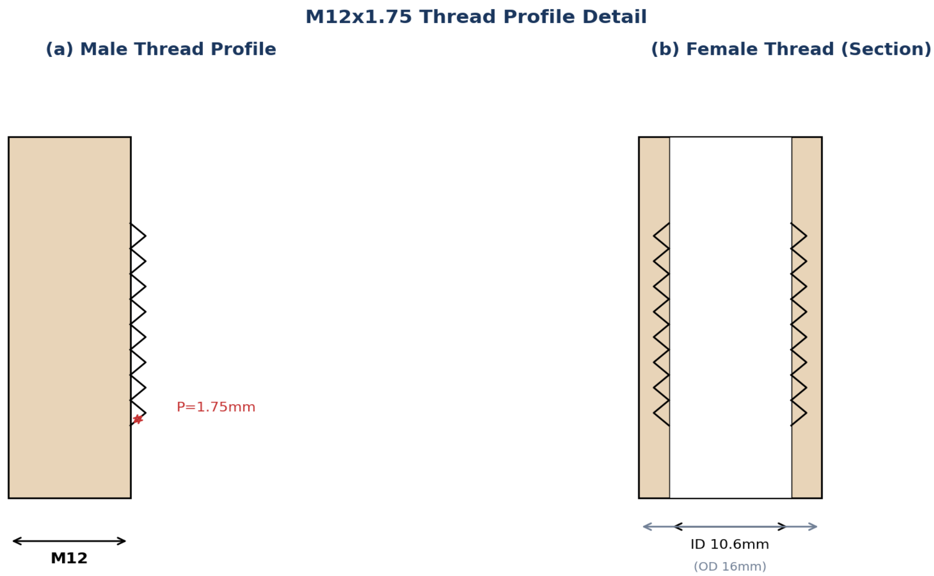


Figure 5. M12x1.75 thread profile detail showing (a) male thread external profile and (b) female thread cross-section. Pitch of 1.75mm provides good engagement with 12-15mm thread length. Male threads print at 12.2mm OD for die cutting; female threads print at 10.5mm ID for tapping.

Parameter	Value
Thread Type	M12x1.75 ISO Standard
Pitch	1.75 mm
Major Diameter	12.0 mm
Engagement Length	12-15 mm
Print Oversize (Male)	12.2 mm (for Die cutting)
Print Undersize (Female)	10.5 mm hole (for Tapping)

Table 3. Thread specifications for modular connections.

5.5 Coil Mounting and Ferrite Cores

The MIT sensing coils are wound onto ferrite rod cores positioned along the probe body. This configuration keeps coils internal to the 16mm profile, adding only 1-2mm to the rod OD with potting. Coils are positioned orthogonally (90 degree separation) to minimize direct coupling between TX and RX elements.

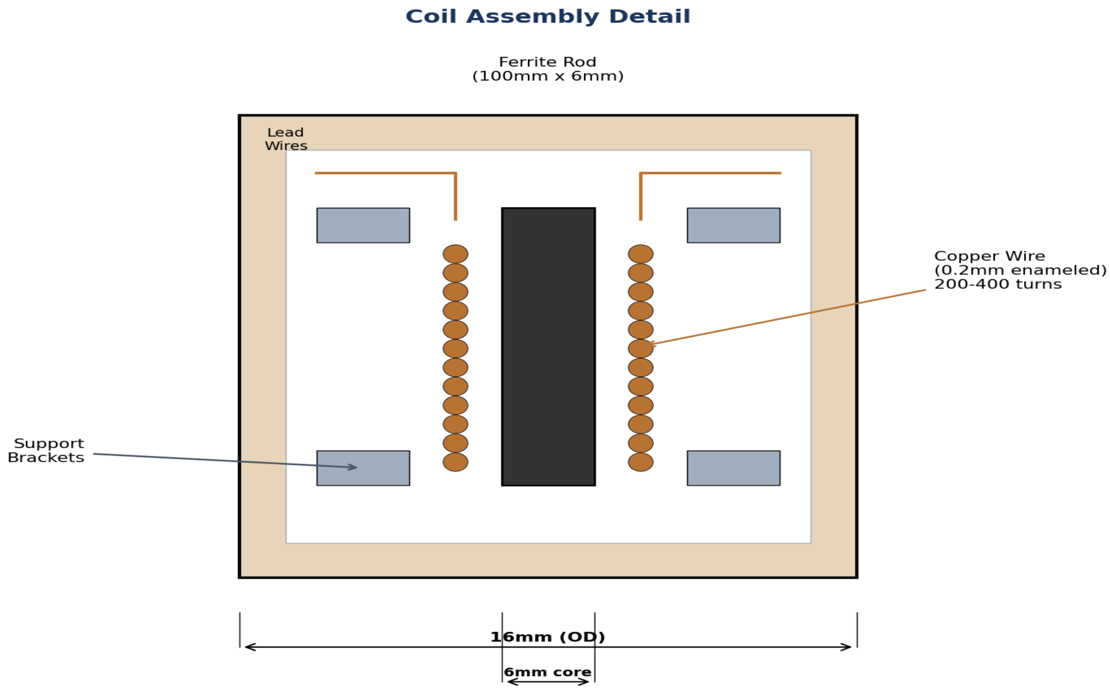


Figure 6. Coil assembly detail showing ferrite rod core (100mm x 6mm) with copper wire windings (200-400 turns of 0.2mm enameled wire). Support brackets maintain alignment within the probe cavity. Lead wires route to the surface junction box.

Parameter	Specification
Diameter	6-8 mm
Length	40-80 mm
Material	MnZn ferrite
Quantity	1-2 per probe (TX/RX)

Table 4. Ferrite core specifications.

Parameter	Specification
Wire Gauge	34-38 AWG (fine wire)
Turns	200-400 turns
Target Inductance	1-2 mH
Target Q Factor	>20

Table 5. Coil winding specifications.

5.6 ERT Ring Electrodes

Electrical Resistivity Tomography (ERT) electrodes are implemented as narrow stainless steel or copper ring bands mounted on 3D-printed insulating collars. The rings are flush-mounted to maintain the smooth probe profile. Multiple rings (typically 2-3 per probe) enable various measurement configurations.

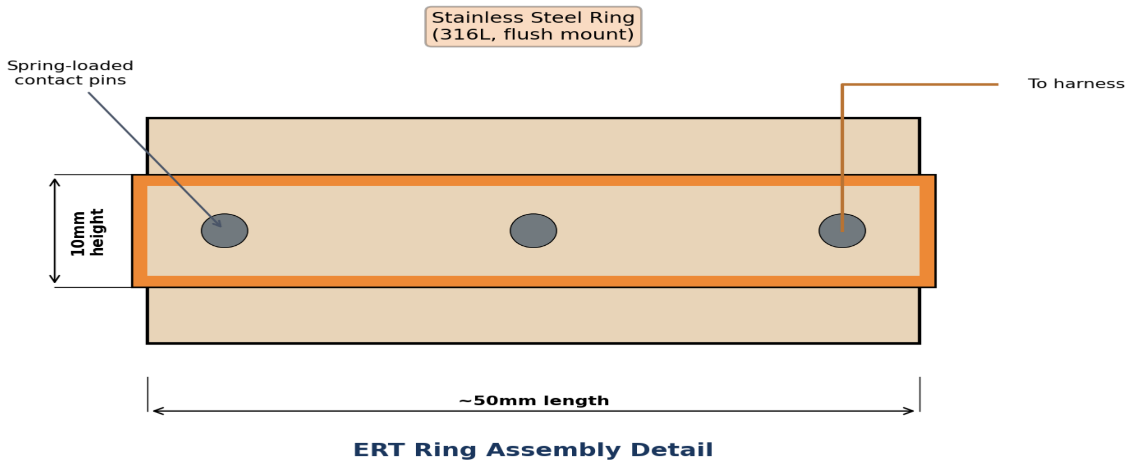


Figure 7. ERT ring collar assembly showing stainless steel ring (316L) flush-mounted on insulating collar. Spring-loaded contact pins ensure reliable electrical connection. Ring dimensions: 5mm width x 16mm OD, approximately 50mm collar length.

Parameter	Value
Ring Material	Stainless steel (316L) or copper
Ring Width	3-5 mm (narrow bands)
Ring Thickness	0.5-1 mm
Diameter	Match rod OD (16 mm)
Quantity	2-3 rings per probe
Minimum Spacing	0.3 m between rings

Table 6. ERT ring electrode specifications.

Position	Distance from Tip
Ring A (Upper)	0.5 m
Ring B (Mid)	1.5 m
Ring C (Deep)	2.5-3.0 m (optional)

Table 7. Standard ERT ring mounting positions.

5.7 Junction Box Design

The surface junction box serves as the termination point for all probe wiring. It contains no active electronics - only passive connections via a terminal block. This keeps the probe lightweight and simple while enabling field serviceability. All 'smart' electronics reside in the central hub at the surface.

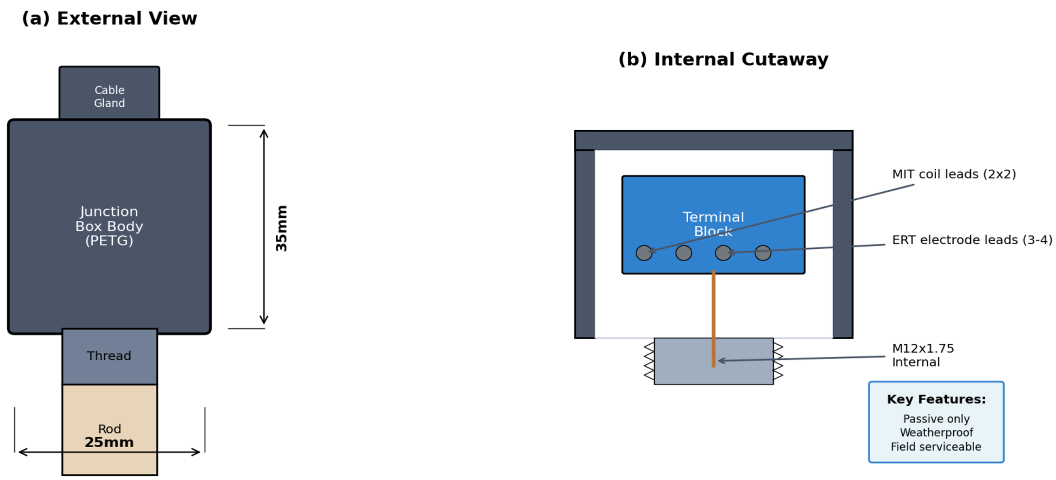


Figure 8. Junction box design showing (a) external view with cable gland and weatherproof body, and (b) internal cutaway revealing terminal block for MIT coil and ERT electrode connections. M12x1.75 internal thread mates with probe rod.

Dimension	Value
Diameter	25 mm
Height	35 mm
Thread	Internal M12x1.75 (bottom)
Material	PETG or ABS (weatherproof)
Features	Terminal block mount, cable gland

Table 8. Surface junction box specifications.

5.8 Probe Cross-Section Detail

The complete probe assembly integrates all components into a unified 16mm OD profile. The cross-section reveals the internal arrangement of coils, ERT rings, threaded joints, and wiring passages. This dense packing enables full sensing capability while minimizing ground disturbance.

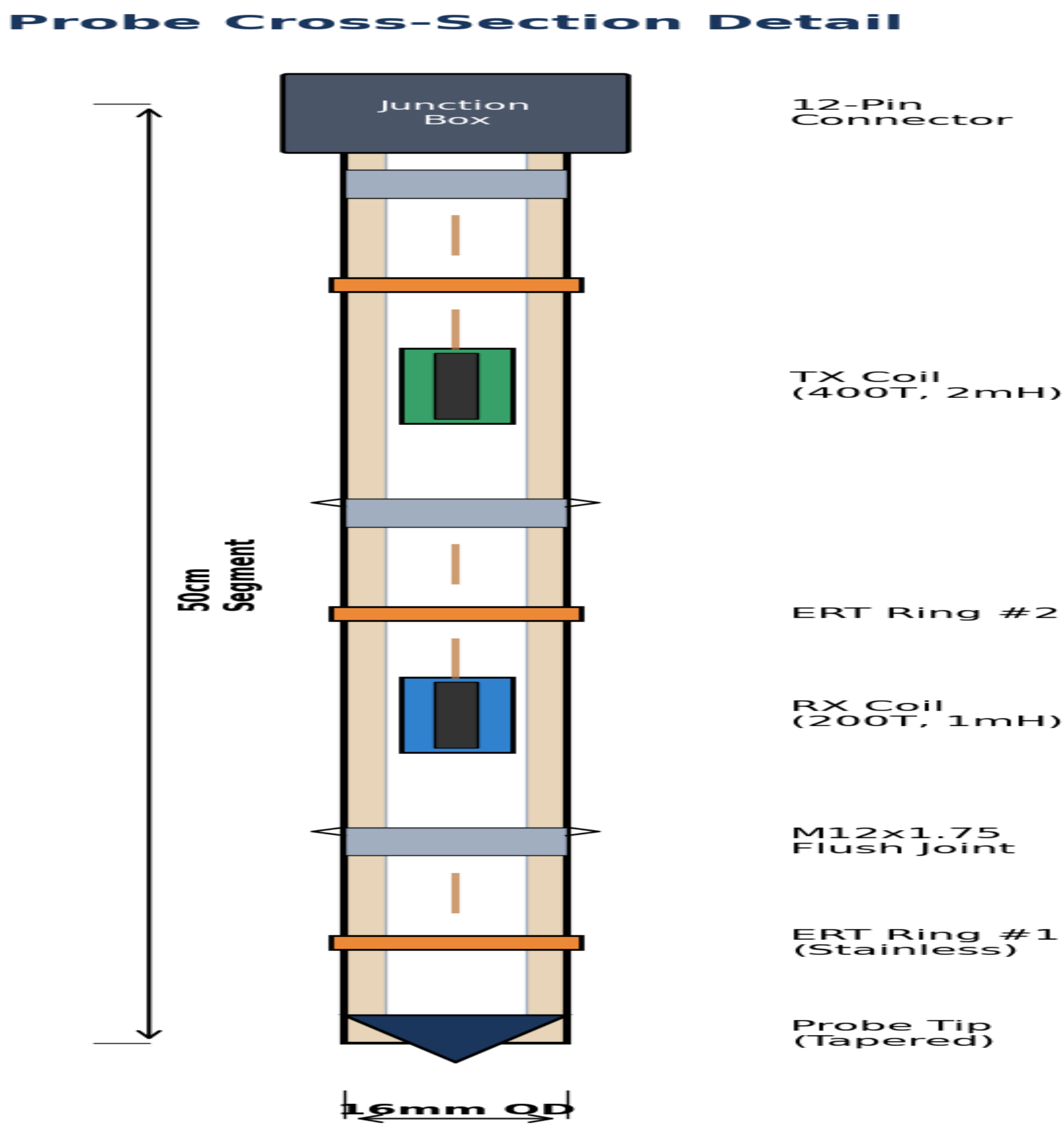


Figure 9. Detailed probe cross-section showing complete internal architecture. From bottom: tapered tip, ERT ring positions, RX coil with ferrite core, M12 threaded joints, TX coil assembly, and junction box connection. Standard 50cm segment shown.

5.9 Manufacturing Procedures

5.9.1 3D Printing Guide

All plastic components are designed for FDM 3D printing with specific settings optimized for thread quality and structural integrity. PETG or ASA material is required for impact resistance and UV stability. Critical: threads require post-processing with tap and die tools.

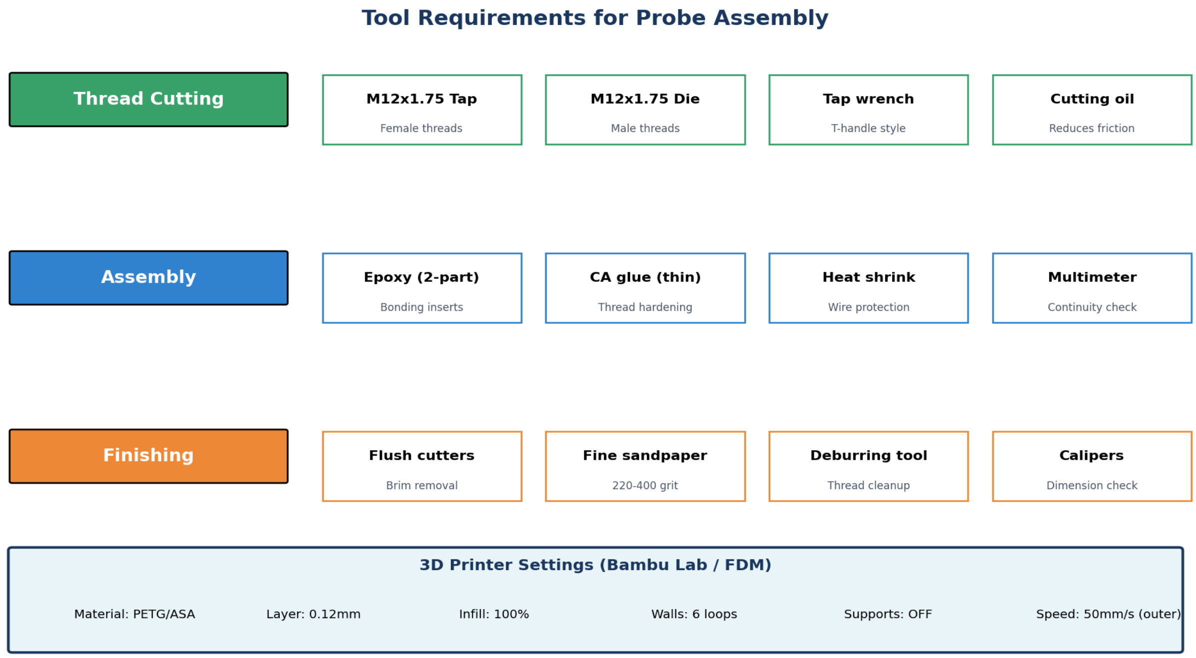


Figure 10. Tool requirements for probe assembly including thread cutting tools (M12x1.75 tap and die), assembly supplies (epoxy, heat shrink), and finishing tools. 3D printer settings shown for Bambu Lab / FDM machines.

Setting	Value	Notes
Material	PETG or ASA	Required for impact/UV
Layer Height	0.12mm	Critical for threads
Infill	100% (Solid)	Critical for strength
Walls	6 Loops	Solid threaded regions
Supports	DISABLED	Use built-in scaffolding
Speed	50mm/s outer wall	Quality over speed

Table 9. Recommended 3D printer settings for probe components.

5.9.2 Thread Post-Processing

Thread Cutting Procedure
• Male threads: Print at 12.2mm OD, cut with M12x1.75 Die • Female threads: Print at 10.5mm hole, cut with M12x1.75 Tap • Always use cutting oil to reduce friction • Cut slowly, back out frequently to clear chips • Test fit before epoxy assembly

5.10 Insertion Methods

Four primary insertion methods accommodate different soil conditions. Method selection depends on soil type, target depth, and available equipment. The pilot rod method requires complete removal of metal before measurements.

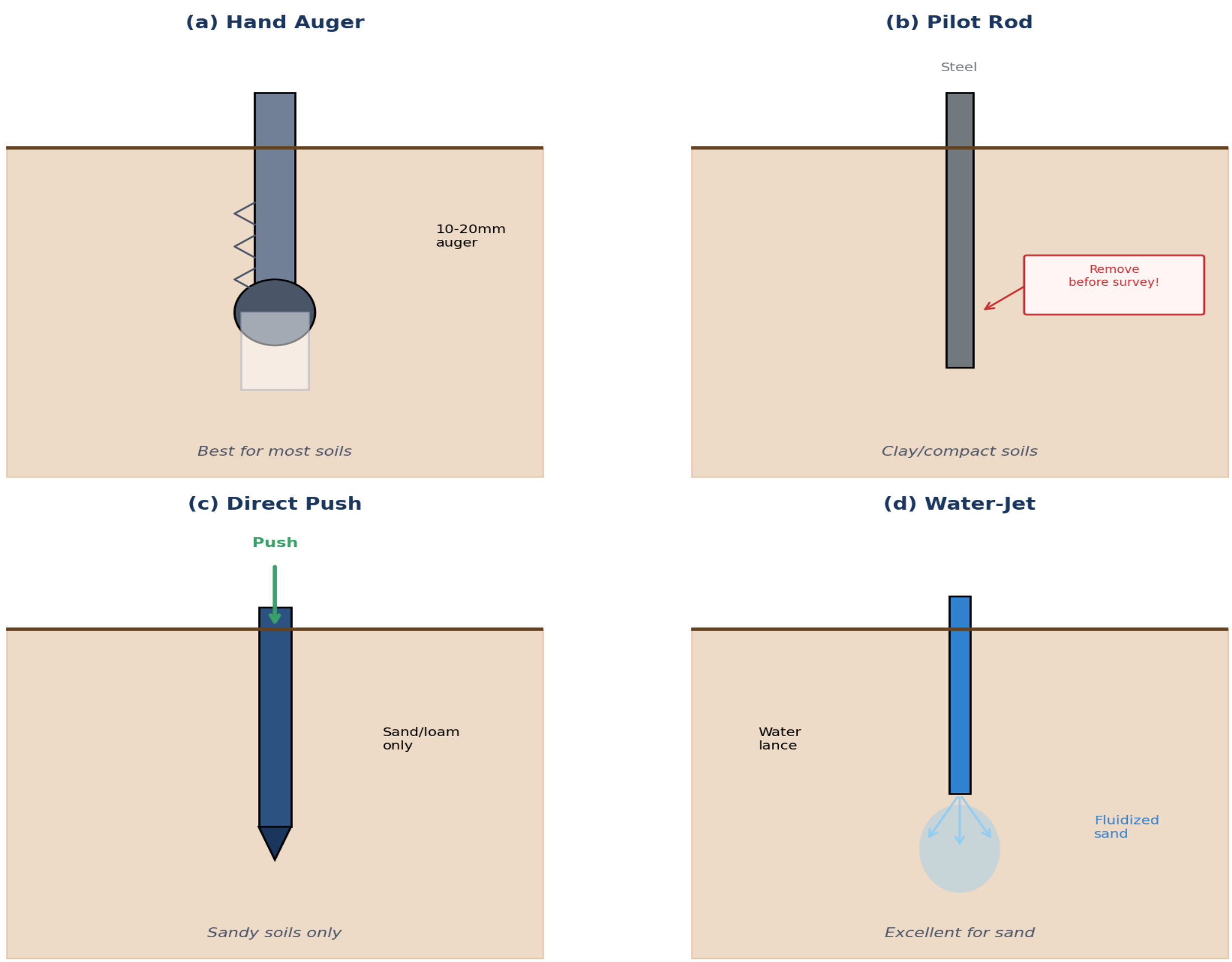


Figure 11. Probe insertion methods: (a) Hand auger for most soils using 10-20mm auger; (b) Pilot rod for compact soils - must remove metal before survey; (c) Direct push in sandy soils only; (d) Water-jet method for excellent sand penetration with minimal disturbance.

5.11 Assembly Sequence

Probe assembly follows a bottom-to-top sequence with all components screwing together via M12 threads. The modular design enables field assembly and allows replacement of individual segments without rebuilding the entire probe.

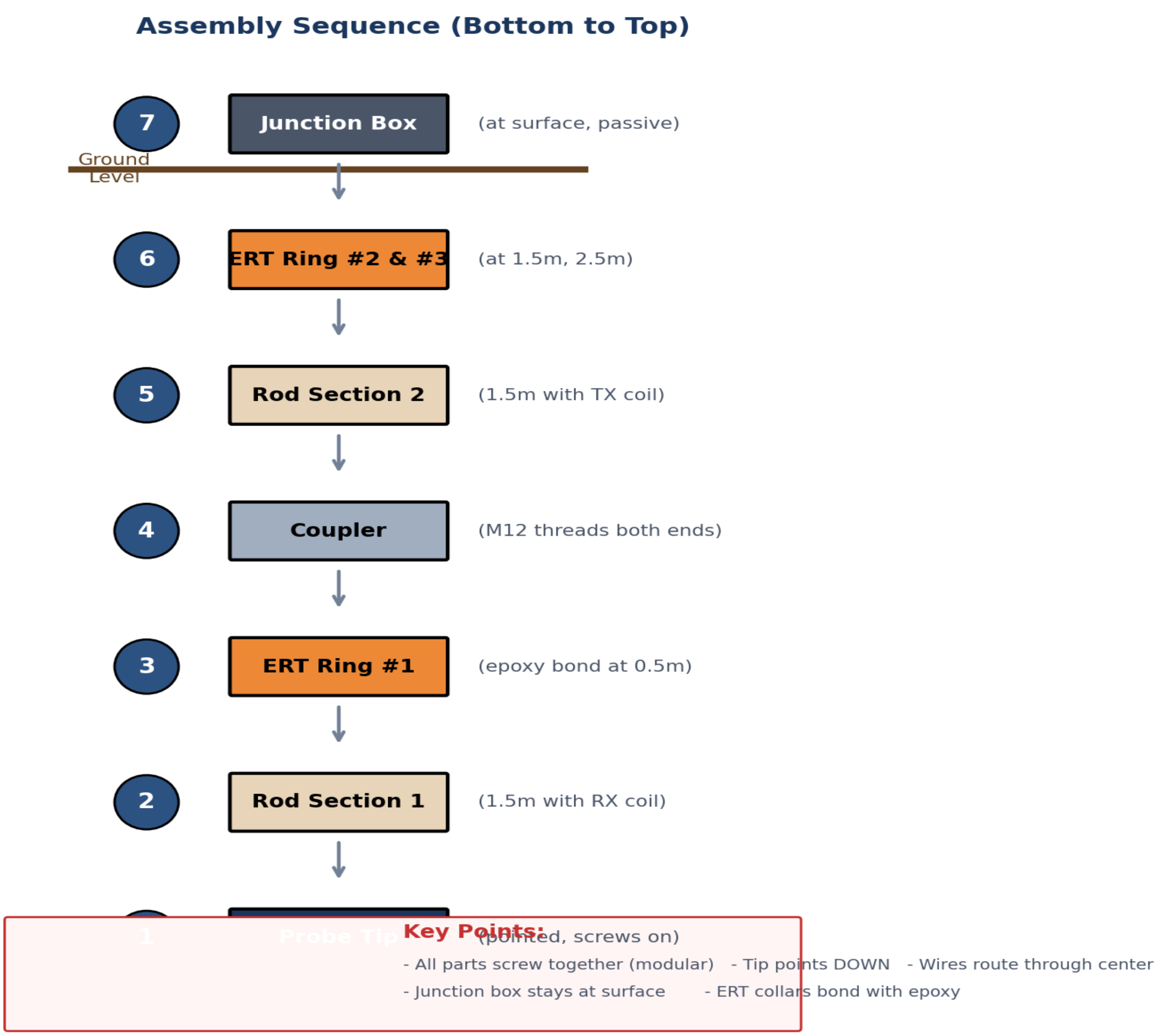


Figure 12. Assembly sequence from bottom to top: (1) Probe tip pointing down, (2) Bottom rod segment with RX coil, (3) First ERT ring at 0.5m, (4) Coupler joint, (5) Top rod segment with TX coil, (6) Additional ERT rings, (7) Junction box at surface level.

5.12 Advantages of Micro-Probe Design

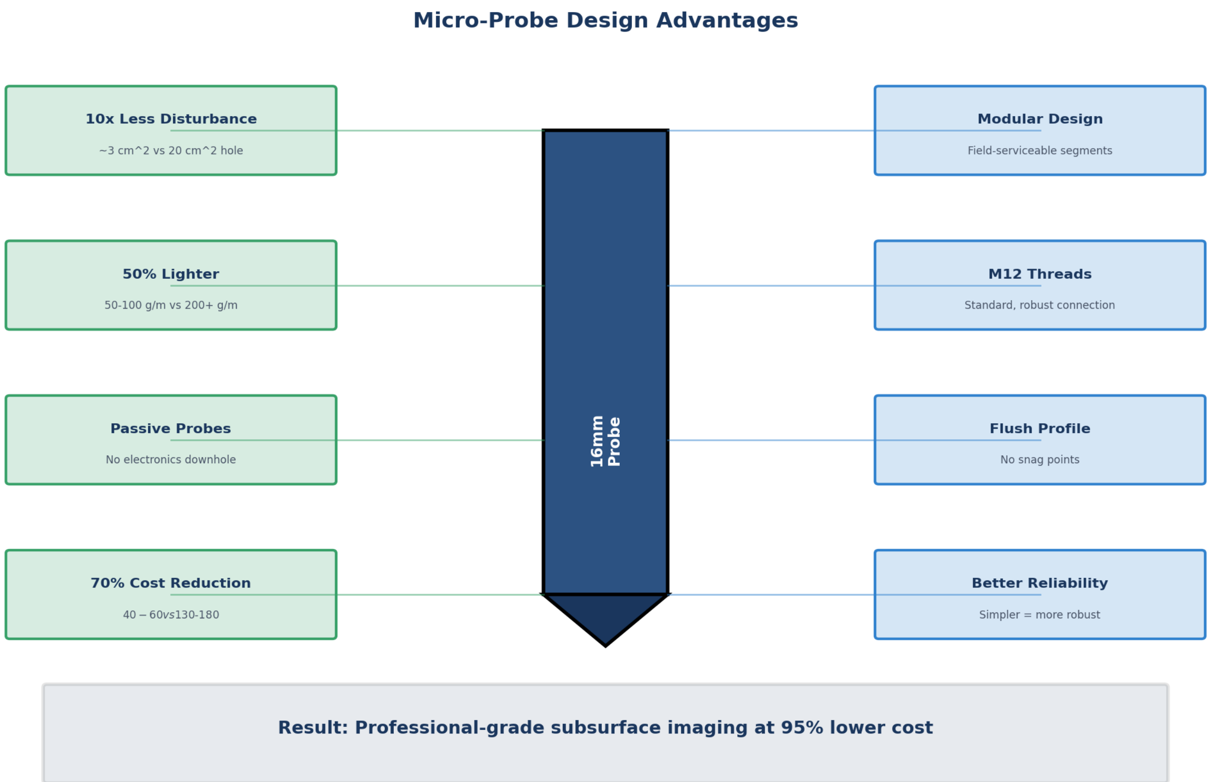


Figure 13. Summary of micro-probe design advantages including 10x less disturbance, modular field-serviceable construction, passive probes with no downhole electronics, and 70% cost reduction compared to traditional designs.

- **Strength:** 16mm OD allows for robust M12 threads
- **Modularity:** Sensor spacing determined by rod segment length
- **Manufacturability:** Sensors built into printed parts, not glued onto rod
- **Smooth Profile:** Flush connections prevent snagging during insertion/extraction
- **Field Serviceable:** Replace individual segments without rebuilding entire probe
- **Simpler Assembly:** No electronics in probe
- **Lighter Weight:** ~50-100 g per meter (vs 200-250 g)
- **Easier Insertion:** Smaller diameter, less force needed
- **Lower Cost:** ~$40-60 per probe (vs $130-180)
- **Better Reliability:** Passive probes more robust
- **Minimal Intrusion:** ~10x less disturbance than 25mm design

References

[1] HIRT Development Team (2026). HIRT Whitepaper: Hybrid Impedance-Resistivity Tomography System. Section 7: Assembly and Wiring.

[2] HIRT Development Team (2026). HIRT Whitepaper: Hybrid Impedance-Resistivity Tomography System. Section 6: Electronics and Circuits.

[3] ISO 261:1998. ISO general purpose metric screw threads - General plan.

[4] ASTM D2584. Standard Test Method for Ignition Loss of Cured Reinforced Resins (Fiberglass specifications).

Section 6: Electronics & Circuits

MIT TX/RX Chains, ERT Circuits, Power Distribution, and Signal Processing

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

6.1 Overview

This section consolidates all circuit designs for the HIRT system, including the MIT (Magneto-Inductive Tomography) circuits, ERT (Electrical Resistivity Tomography) circuits, and base hub electronics. The design uses **centralized electronics with passive probes**: all active components reside in the surface hub, while probes contain only coils and electrodes.

This architecture offers significant advantages: lower per-probe cost, easier maintenance, better reliability (passive probes are more robust), centralized firmware updates, and simplified probe construction. The trade-off is increased cabling complexity for the multi-probe harness.

6.2 System Block Diagram

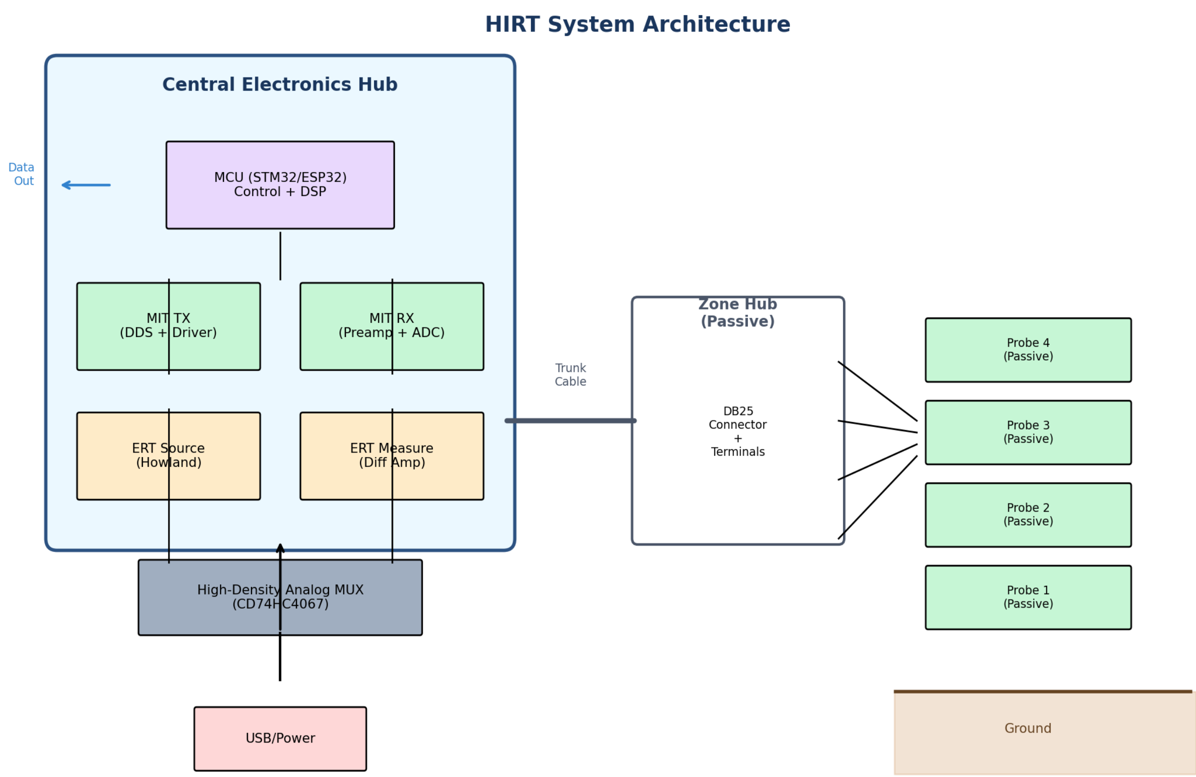


Figure 1. Complete HIRT system architecture showing the central electronics hub, zone wiring strategy, and passive probe connections. All signal processing occurs in the hub; probes are purely passive sensors.

The central hub contains: (1) MCU for control and DSP, (2) MIT transmitter chain (DDS + power driver), (3) MIT receiver chain (preamp + instrumentation amplifier + ADC), (4) ERT current source and voltage measurement, and (5) high-density analog multiplexers. These connect via DB25 trunk cables to passive **Zone Hubs**, which then distribute signals to individual probes.

6.3 MIT Transmit (TX) Chain

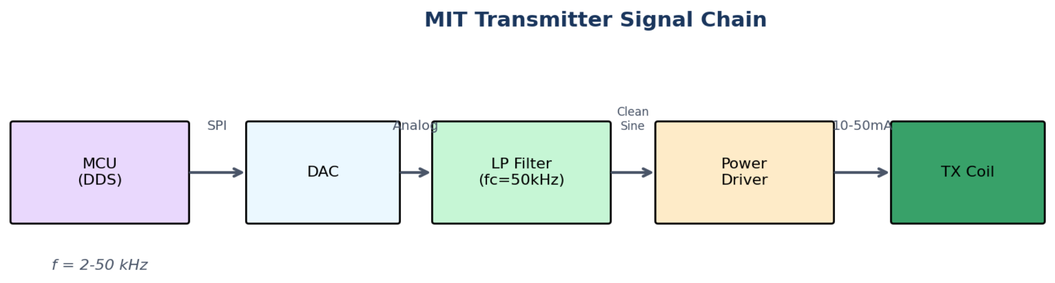


Figure 2. MIT transmitter signal chain from MCU through DDS, filtering, and power driver to the TX coil. Operating frequency range is 2-50 kHz.

6.3.1 DDS Sine Generator

The transmit chain begins with a Direct Digital Synthesis (DDS) generator, the AD9833. This IC generates precise sine waves from 0.1 Hz to 12.5 MHz with 28-bit frequency resolution. For HIRT, the operating range is 2-50 kHz, with lower frequencies (2-10 kHz) preferred for deeper penetration.

Parameter	Specification
Part Number	AD9833BRMZ
Frequency Range	0.1 Hz to 12.5 MHz
Output Level	0.6 V RMS sine wave
Interface	SPI (10 MHz max)
Resolution	28-bit frequency, 12-bit phase
Power Supply	2.3-5.5V, 3 mA typical

Table 1. AD9833 DDS Generator Specifications

6.3.2 TX Power Driver

The DDS output is amplified by an OPA454 or OPA2277 operational amplifier configured as a non-inverting amplifier. The gain is set by external resistors to provide 2-10x amplification, delivering 10-50 mA into the TX coil at 0-5 V RMS. The driver bandwidth (2.5 MHz) easily accommodates the operating frequency range.

Parameter	OPA454	OPA2277
Gain (configurable)	2-10x	2-10x
Output Current	+/-2.5 A peak	+/-20 mA
Bandwidth	2.5 MHz	1 MHz
Slew Rate	19 V/us	0.8 V/us
Power Supply	+/-5V to +/-40V	+/-2V to +/-18V

Table 2. TX Driver Op-Amp Options

6.4 MIT Receive (RX) Chain

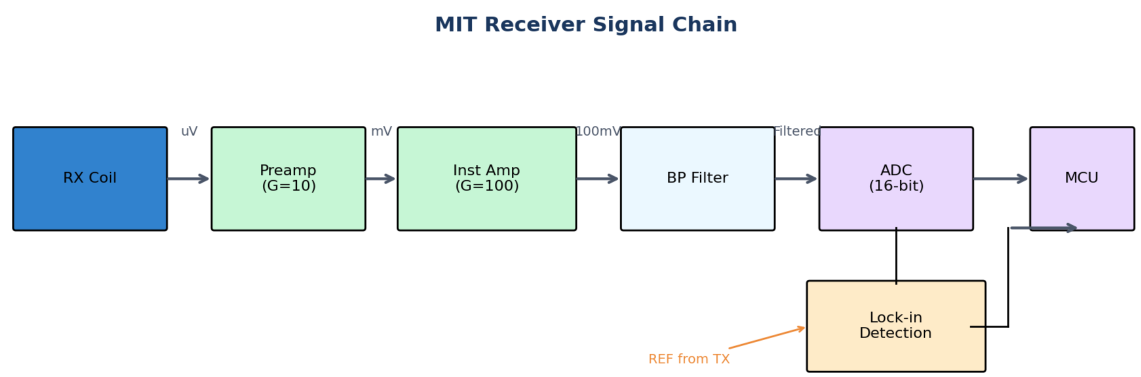


Figure 3. MIT receiver signal chain from RX coil through preamplifier, instrumentation amplifier, band-pass filter, and ADC. Total gain is approximately 1000x (60 dB). Lock-in detection extracts the signal at the reference frequency.

6.4.1 RX Preamplifier (AD620)

The receive coil output (microvolts to millivolts) connects to an AD620 instrumentation amplifier. This device provides excellent common-mode rejection (100 dB minimum) and low noise (9 nV/sqrt(Hz)). Gain is set by a single resistor R_G according to: G = (49.4k / R_G) + 1.

Target Gain	R_G Value	Notes
G = 10	5.49 k-ohm	Standard setting
G = 100	499 ohm	High sensitivity
G = 1000	49.9 ohm	Maximum gain

Table 3. AD620 Gain Resistor Selection

6.4.2 Instrumentation Amplifier (INA128)

A second gain stage uses the INA128, providing additional amplification (typically 10-100x) and further common-mode rejection. The combined gain of both stages can reach 10,000x (80 dB), sufficient to amplify microvolt signals to ADC input levels.

6.4.3 Signal Level Progression

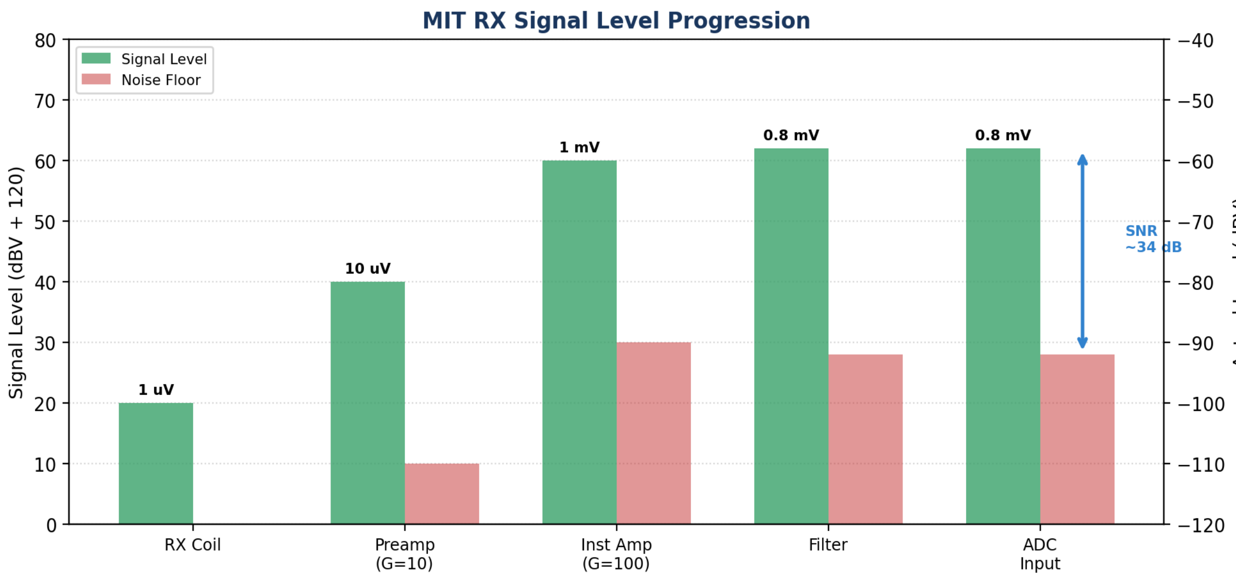


Figure 4. Signal level progression through the MIT RX chain. The signal starts at approximately 1 uV at the coil and is amplified to 0.8 mV at the ADC input. The noise floor also rises but at a slower rate, maintaining adequate SNR.

6.5 Lock-In Detection

Lock-in detection is essential for extracting weak MIT signals from noise. The HIRT system uses **digital lock-in detection** implemented in the MCU, which offers flexibility, software configurability, and no analog drift. The technique multiplies the received signal by reference sine and cosine waveforms at the excitation frequency, then low-pass filters to extract the in-phase (I) and quadrature (Q) components.

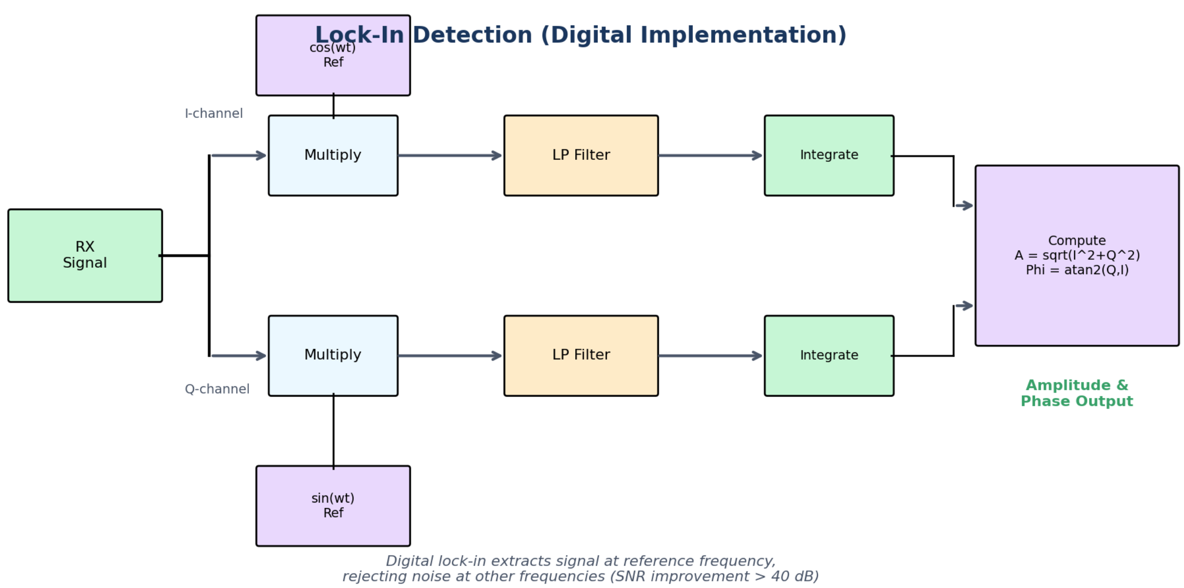


Figure 5. Digital lock-in detection block diagram. The RX signal is multiplied by reference sine (Q-channel) and cosine (I-channel) signals, then filtered and integrated. Amplitude A = sqrt(I^2 + Q^2) and phase Phi = atan2(Q,I) are computed from the I/Q outputs.

The lock-in algorithm provides exceptional noise rejection (> 40 dB improvement) by responding only to signals at the exact reference frequency. This allows detection of MIT signals buried deep in noise, critical for weak responses from distant or low-conductivity targets.

6.5.1 Digital Lock-In Algorithm

```
// Simplified digital lock-in implementation
float I_sum = 0, Q_sum = 0;
for (int i = 0; i < N_samples; i++) {
float sample = read_adc();
float ref_I = sin(2 * PI * f * i / Fs);
float ref_Q = cos(2 * PI * f * i / Fs);
I_sum += sample * ref_I;
Q_sum += sample * ref_Q;
}
float amplitude = sqrt(I_sum*I_sum + Q_sum*Q_sum) / N_samples;
float phase = atan2(Q_sum, I_sum);
```

6.6 ERT Current Source (Howland Pump)

The ERT subsystem injects controlled current into the ground through electrode rings and measures the resulting voltage distribution. The current source uses a **Howland current pump** topology, which provides high output impedance (>1 M-ohm) and stable current regardless of load variations.

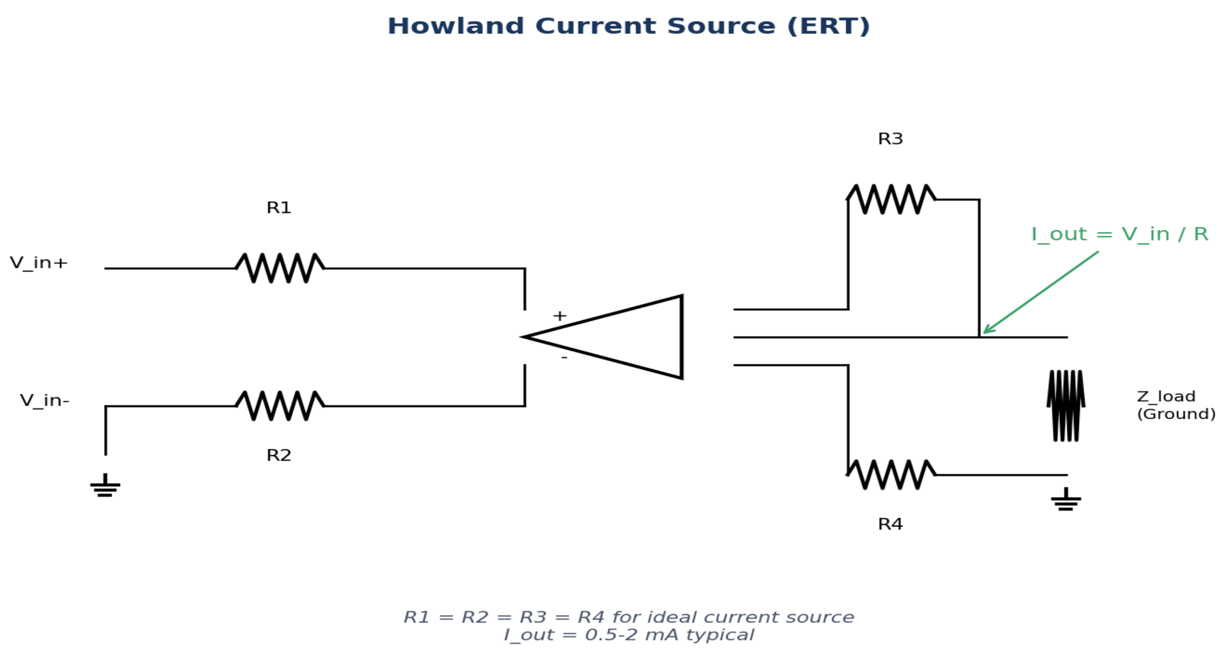


Figure 6. Howland current pump circuit for ERT measurements. When R1=R2=R3=R4, the output current is I_out = V_in / R_sense, independent of load impedance. A precision 2.5V reference (REF5025) provides stable input voltage.

Parameter	Specification
Output Current	0.5-2 mA (adjustable)
Current Accuracy	+/- 5%
Compliance Voltage	+/- 10V minimum
Output Impedance	> 1 M-ohm
Load Range	100 ohm - 10 k-ohm
Polarity Reversal	Programmable (0.5 Hz)

Table 4. ERT Current Source Specifications

6.6.1 Polarity Reversal

Electrode polarization causes measurement drift in DC systems. To mitigate this, HIRT reverses the current polarity every 2 seconds using a DPDT relay (G5V-2-H1) or solid-state switch (ADG1219). Positive and negative measurements are averaged to cancel polarization effects.

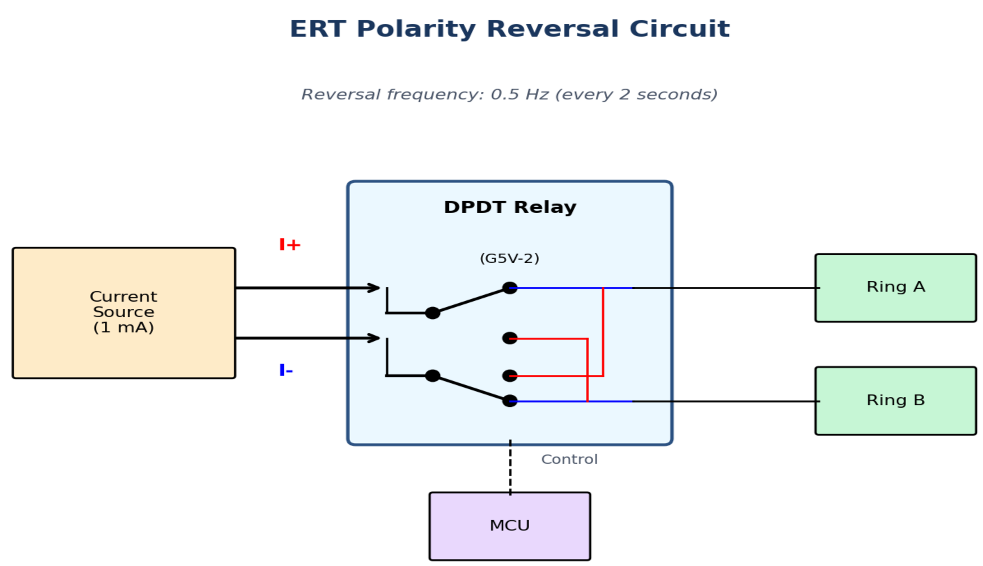


Figure 7. ERT polarity reversal circuit using a DPDT relay. The relay alternates current direction between Ring A and Ring B every 2 seconds, eliminating electrode polarization artifacts from the measurement.

6.7 ADC Interface

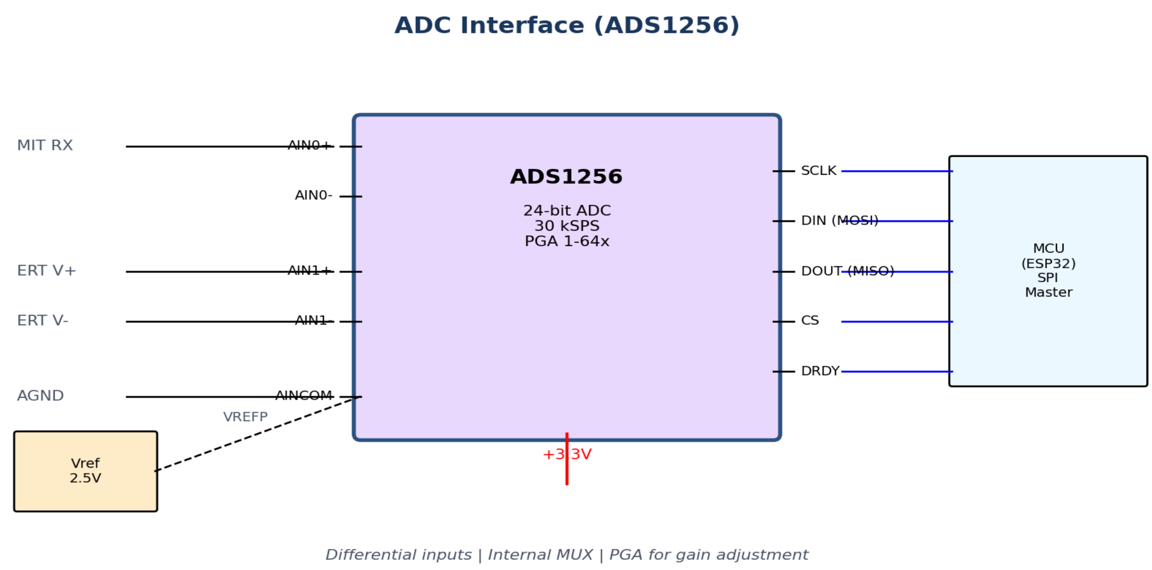


Figure 8. ADS1256 ADC interface showing differential analog inputs for MIT and ERT signals, SPI connection to MCU, and reference voltage. The 24-bit resolution and internal PGA provide excellent dynamic range.

Parameter	ADS1256 Specification
Resolution	24 bits
Sample Rate	30 kSPS maximum
Noise	0.6 uV RMS (at 100 SPS)
Interface	SPI
Internal PGA	1, 2, 4, 8, 16, 32, 64x
Input Channels	8 single-ended or 4 differential

Table 5. ADS1256 ADC Specifications

6.8 Multiplexer Switching

With up to 24 probes in a typical array, the HIRT system requires a scalable multiplexing strategy. The design uses cascaded CD4051 8:1 analog multiplexers controlled by MCU GPIO pins. Each TX and RX signal path has its own multiplexer chain, allowing independent selection of transmit and receive probes.

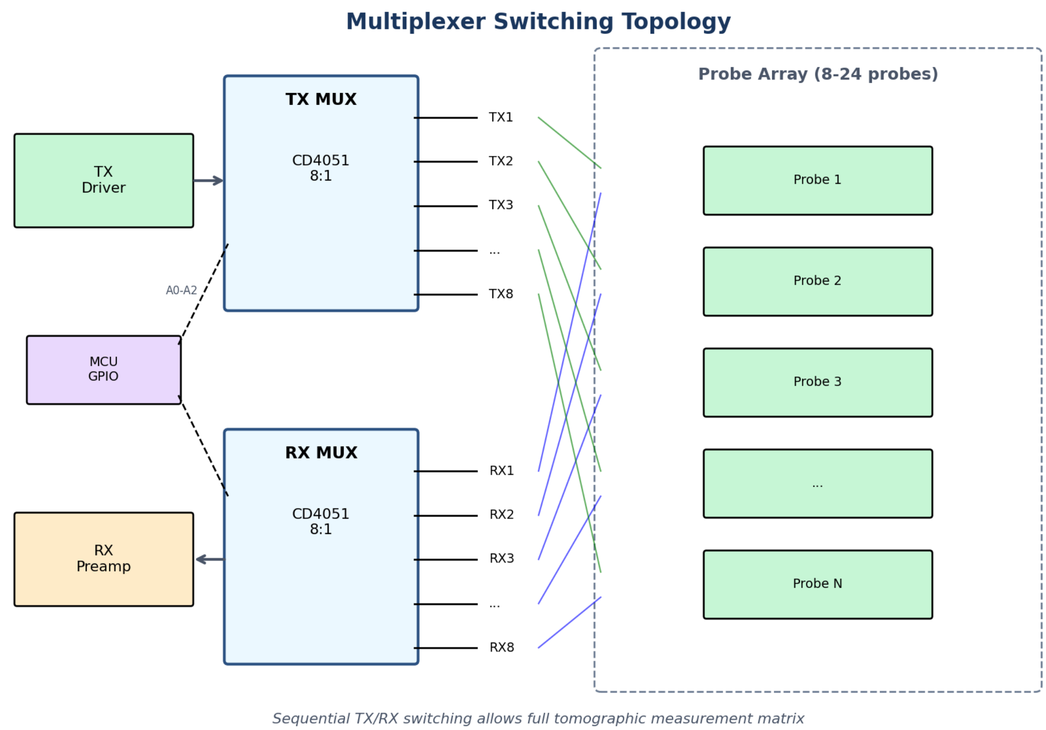


Figure 9. Multiplexer switching topology for probe selection. Separate TX and RX multiplexers allow any TX-RX probe combination to be measured. MCU GPIO controls multiplexer address lines (A0-A2).

6.9 Power Distribution

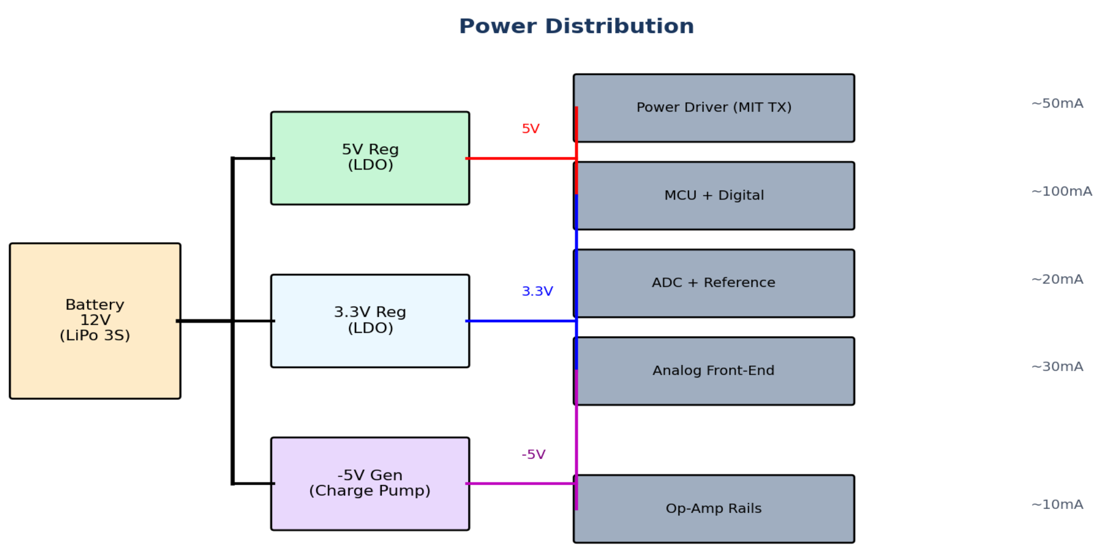


Figure 10. Power distribution from 12V battery through regulators to various subsystems. Total system current is approximately 200 mA, providing several hours of operation from a 3S LiPo battery.

Rail	Voltage	Current	Purpose
+12V (Battery)	11.1-12.6V	200 mA total	System input
+5V (LDO)	5.0V	50 mA	Power driver, references
+3.3V (LDO)	3.3V	100 mA	MCU, ADC, digital
-5V (Charge pump)	-5.0V	10 mA	Op-amp negative rail

Table 6. Power Rail Specifications

6.10 Noise Filtering Stages

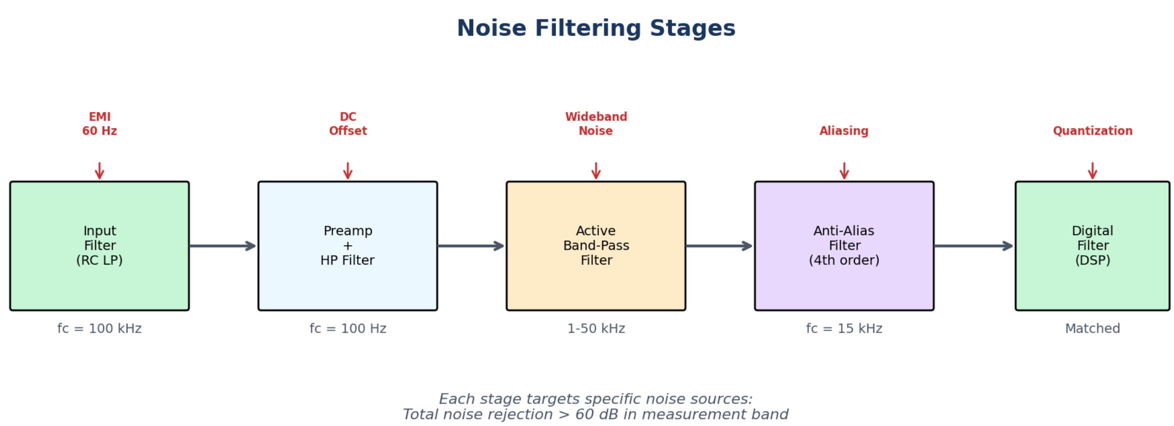


Figure 11. Cascaded noise filtering stages in the signal chain. Each stage targets specific noise sources: EMI, DC offsets, wideband noise, aliasing, and quantization noise. Combined rejection exceeds 60 dB.

Noise reduction is critical for MIT measurements where signal levels can be in the microvolt range. The filtering strategy employs multiple stages:

- **Input RC filter (fc=100kHz):** Blocks RF interference and high-frequency EMI
- **High-pass filter (fc=100Hz):** Removes DC offsets and 60Hz pickup
- **Active band-pass (1-50kHz):** Passes only the measurement band
- **Anti-aliasing filter (fc=15kHz):** Prevents aliasing in ADC sampling
- **Digital matched filter:** Optimizes SNR in post-processing

6.11 Shielding and Ground Loop Prevention

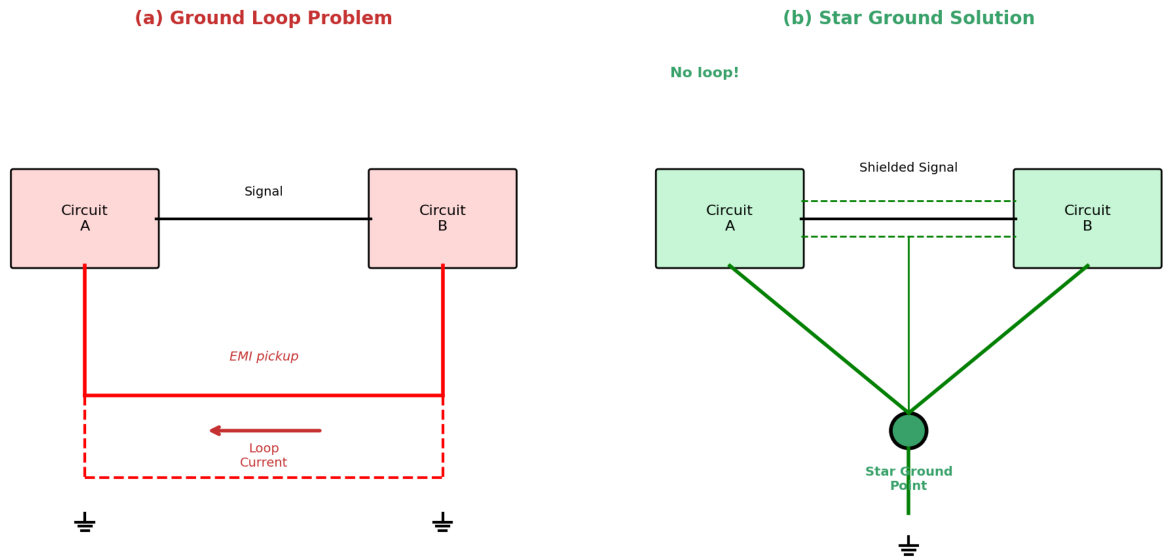


Figure 12. Ground loop prevention techniques. (a) shows the problem: multiple ground paths create loops that pick up EMI. (b) shows the solution: star grounding with a single connection point eliminates loops.

Proper grounding is essential for achieving low-noise measurements. The HIRT design follows these best practices:

- **Star grounding:** All ground returns connect at a single point near the ADC
- **Separate ground planes:** Analog and digital grounds are split on the PCB
- **Shielded cables:** All signal cables use twisted-pair with overall shield
- **Single-point shield termination:** Shields grounded at hub end only
- **Minimum loop area:** Signal and return paths routed together

6.12 PCB Layout Guidelines

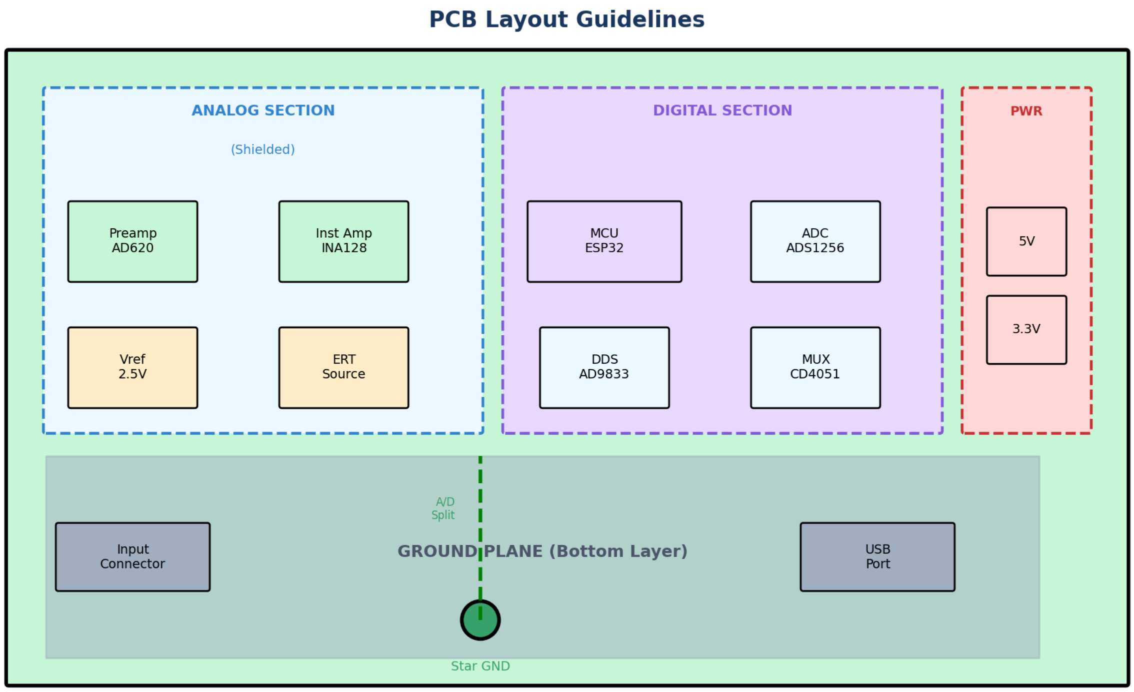


Figure 13. Recommended PCB layout showing component placement zones. The analog section (shielded) is physically separated from digital circuits. Ground plane spans the bottom layer with analog/digital split connected at a star point.

6.12.1 Layout Rules

1. Place bypass capacitors (100nF) within 5mm of each IC power pin
2. Route analog signals with minimum trace length; avoid crossing digital signals
3. Use differential pairs for RX coil signals with matched length
4. Keep TX and RX signal paths physically separated (>10mm)
5. Provide shielding (copper pour) around sensitive analog circuits
6. Use wide traces (>20 mil) for power distribution
7. Connect analog and digital ground planes at a single star point near the ADC

6.13 Key Component Summary

Component	Part Number	Function	Package
DDS	AD9833BRMZ	Signal generator	MSOP-10
TX Driver	OPA454AIDDAR	Coil driver	SOIC-8
Preamp	AD620ARZ	RX preamplifier	SOIC-8
Inst Amp	INA128PAG4	Differential amp	DIP-8
ADC	ADS1256IDBR	24-bit ADC	SSOP-28
Multiplexer	CD4051BE	8-channel mux	DIP-16
MCU	ESP32-WROOM-32	Controller	Module
V-Reference	REF5025AIDGKR	2.5V reference	SOIC-8
LDO	AMS1117-3.3	3.3V regulator	SOT-223

Table 7. Key IC Components

6.14 Connector Pinouts (Probe-to-Zone)

Pin	Signal	Description
1	TX+	To probe TX coil
2	TX-	Return path
3	RX+	Differential RX
4	RX-	Differential RX return
5	Guard	Analog ground
6	Ring A	Upper ERT electrode
7	Ring B	Mid ERT electrode
8	Ring C	Deep electrode
9	ID Sense	Auto-ID resistor
10-11	Spare	Reserved
12	Shield	Cable shield clamp

Table 8. 12-pin Probe Connector Pinout

6.15 Safety Considerations

ELECTRICAL SAFETY

- Maximum output current limited to 5 mA by design
- Compliance voltage restricted to +/-12V (safe for soil contact)
- Include 10 mA fast-blow fuse on ERT output
- Use opto-isolated relay control for polarity switching
- Ensure proper earth ground connection for safety

6.16 Troubleshooting Guide

Symptom	Likely Cause	Solution
No TX output	DDS not initialized	Check SPI connection, verify clock
Weak RX signal	Gain too low	Verify R_G resistor, check amplifier rails
Noisy readings	Ground loops	Implement star grounding, shield cables
No ERT current	Open circuit	Check electrode contact, verify relay state
Current drift	Reference unstable	Verify Vref output, add bypass caps
ADC errors	SPI timing	Reduce SPI clock speed, check DRDY timing

Table 9. Common Issues and Solutions

References

[1] Analog Devices. AD9833 Programmable Waveform Generator Data Sheet. Rev. F, 2019.
[2] Texas Instruments. OPA454 High-Voltage, High-Current Operational Amplifier. SBOS328D, 2018.
[3] Analog Devices. AD620 Low Cost, Low Power Instrumentation Amplifier. Rev. H, 2011.
[4] Texas Instruments. INA128 Precision, Low Power Instrumentation Amplifiers. SBOS051B, 2005.
[5] Texas Instruments. ADS1256 Very Low Noise, 24-Bit Analog-to-Digital Converter. SBAS288K, 2013.
[6] Horowitz, P. and Hill, W. The Art of Electronics, 3rd Edition. Cambridge University Press, 2015. Chapter 5: Precision Circuits.
[7] Ott, H.W. Electromagnetic Compatibility Engineering. Wiley, 2009. Chapter 3: Grounding.

Section 7: Assembly and Wiring

Comprehensive Assembly Instructions for HIRT Modular Micro-Probe System

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

7.1 Overview

This section provides comprehensive step-by-step assembly instructions for the HIRT modular micro-probe system (16mm). The modular design allows probes to be built by stacking fiberglass rod segments and 3D-printed sensor modules. The assembly process is designed for field conditions with minimal tooling requirements.

7.2 Parts List

7.2.1 Printed Parts (PETG/ASA)

Part	Qty/Probe	Notes
Male Insert Plug	2	Threaded male screw end
Sensor Module (Female)	2-3	Sensor body with female threads
Probe Tip	1	Pointed nose cone
Top Cap	1	Cable exit/handle

Table 1. 3D-printed probe components

7.2.2 Hardware

Part	Qty/Probe	Notes
Fiberglass Tube	2-3 sections	16mm OD x 12mm ID
Epoxy	As needed	2-part structural (Loctite Marine, JB Weld)
O-rings	4-6	Size for M12 thread shoulder (10mm ID x 1.5mm)
Ferrite Cores	1-2	For MIT coils (6-8mm x 40-80mm)
Magnet Wire	10-20m	30-34 AWG for coil winding
ERT Ring Material	2-3 bands	Stainless steel or copper tape
Cable	3-5m	Multi-conductor shielded

Table 2. Hardware and consumable materials

7.3 Tools Required

Tool	Purpose
Hacksaw or Tube Cutter	Cutting fiberglass tubing
400-grit Sandpaper	Surface preparation
M12x1.75 Tap	Threading female parts
M12x1.75 Die	Threading male parts
Tap Handle	For tap operation
Mixing Cups	For epoxy
Nitrile Gloves	Epoxy handling
Soldering Iron	Wire connections
Multimeter	Testing continuity
Calipers	Measuring dimensions

Table 3. Essential tools for assembly

Recommended Additional Tools

- Bench Vise - Holding parts during tapping
- Thread Cutting Oil - Lubrication for tap/die
- LCR Meter - Coil testing
- Heat Gun - Heat shrink tubing
- Wire Strippers - Cable preparation

7.4 Wiring Architecture

The HIRT system uses a hierarchical wiring architecture designed to manage the complexity of connecting 20-50 passive probes. Rather than routing all probe cables directly to the main hub (which would require 600+ conductors), the system uses a **Zone Wiring Strategy** that aggregates signals through intermediate junction boxes.

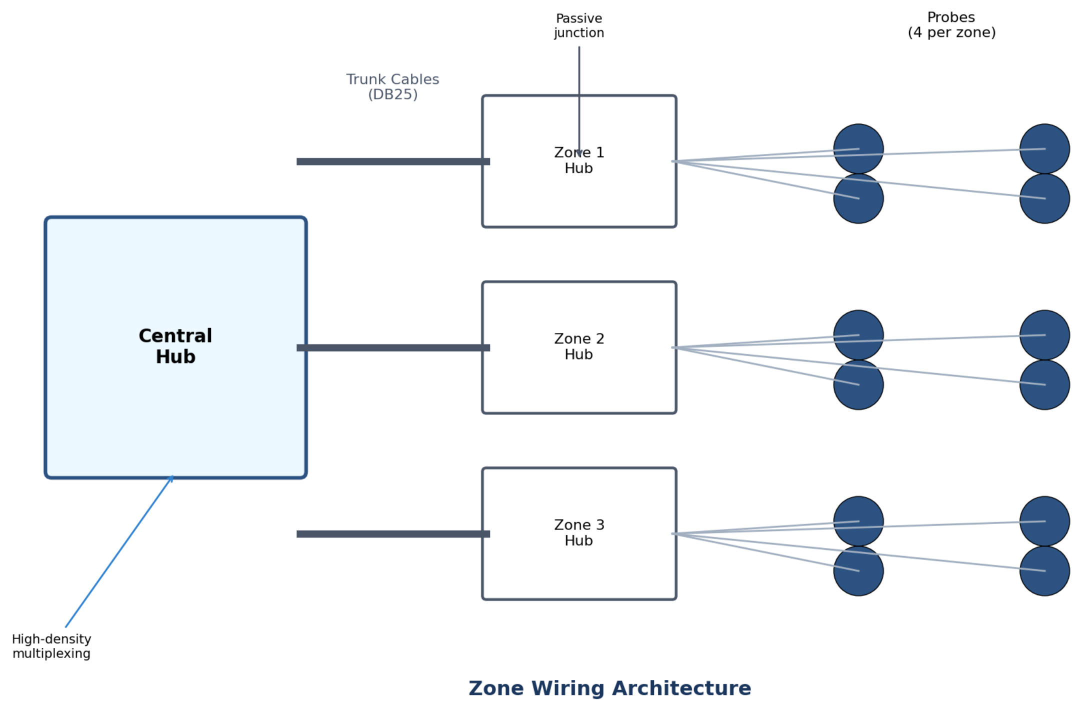


Figure 1. Zone wiring architecture showing probe groupings, zone boxes, and trunk cable routing to the central hub. Each zone aggregates 4 probes through a passive junction box.

7.4.1 System Topology

The zone architecture divides the probe array into manageable groups of 4 probes each. Each group connects to a Zone Box (small passive hub) via individual probe cables. The Zone Box then connects to the Main Hub via a single high-density Trunk Cable. This reduces the number of cables entering the main enclosure from 20+ to just 5-6 trunk cables.

- **Zone Box:** Small IP65 enclosure (100x100mm) with 4 cable glands for probes and 1 DB25 connector for trunk output
- **Trunk Cable:** High-quality shielded 25-conductor cable, 10-20 meters, carrying signals for 4 probes
- **Advantages:** Modular expansion, clean installation, field-ready deployment

7.4.2 Wiring Harness Layout

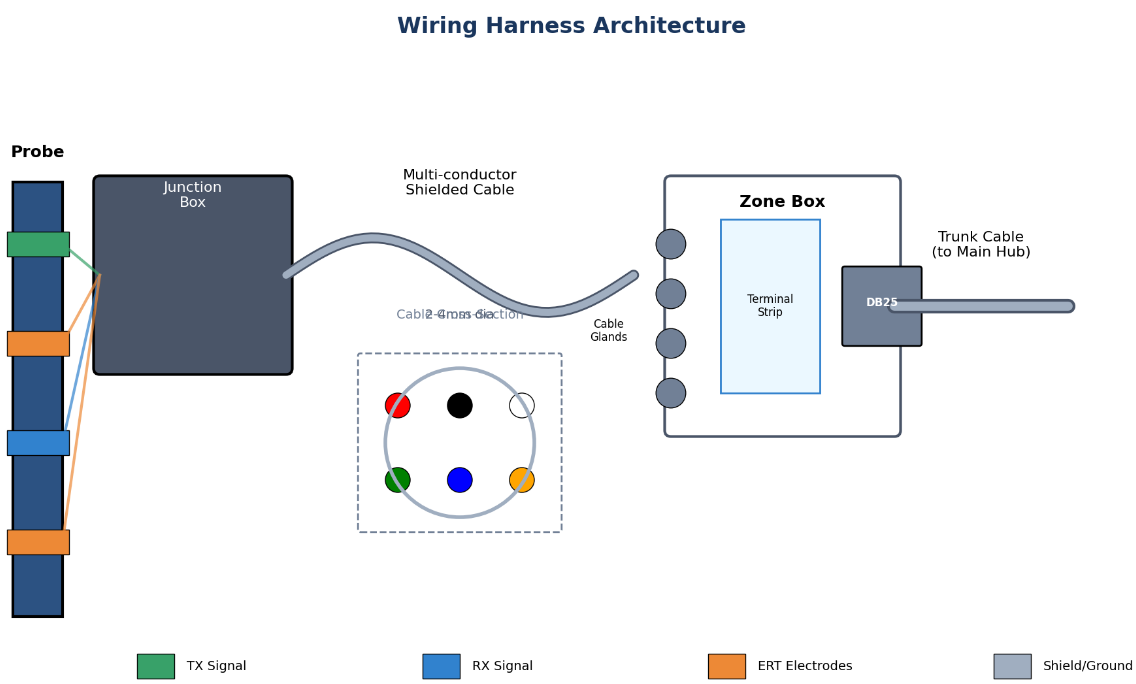
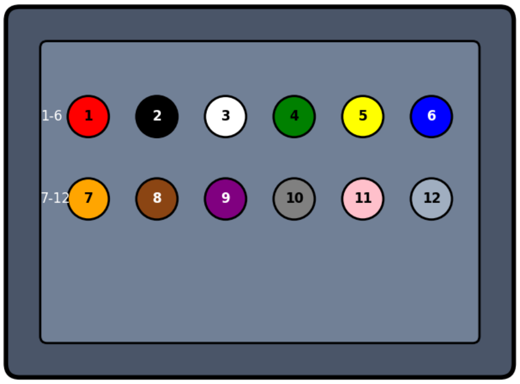


Figure 2. Wiring harness architecture from probe sensors through junction box and zone box to the main hub. The multi-conductor shielded cable (2-4mm diameter) carries all sensor signals.

7.4.3 Connector Pinout Reference

The system uses 12-pin Phoenix Contact connectors (part number 1757248) or equivalent for probe-side connections. The pinout is standardized across all probes to ensure interchangeability and simplify field maintenance.

12-Pin Phoenix Connector Pinout (1757248)



Signal Assignment

Pin	Signal	Color
1	TX+	
2	TX-	
3	RX+	
4	RX-	
5	Guard	
6	Ring A	
7	Ring B	
8	Ring C	
9	ID Sense	
10	Spare+	
11	Spare-	
12	Shield	

Notes:

- Pins 1-4: MIT coil differential pairs
- Pins 5: Guard/reference electrode
- Pins 6-8: ERT ring electrodes
- Pin 9: Probe ID sense (optional)
- Pins 10-11: Reserved for future use
- Pin 12: Cable shield (drain wire)

Figure 3. 12-pin Phoenix connector pinout showing signal assignments and recommended wire colors. Pins 1-4 carry MIT coil differential pairs, pins 6-8 carry ERT electrode signals.

7.4.4 Cable Color Coding

Color	Name	Function
	Green	TX Signal
	Blue	RX Signal
	Red	ERT Current
	Orange	ERT Voltage
	Black	Ground/Shield
	Purple	Power (+12V)
	Gray	Power (GND)

Cable Color Coding Reference

Figure 4. Cable color coding reference for consistent wiring across all probes. Following this standard simplifies troubleshooting and maintenance.

7.4.5 Probe-to-Hub Signal Routing

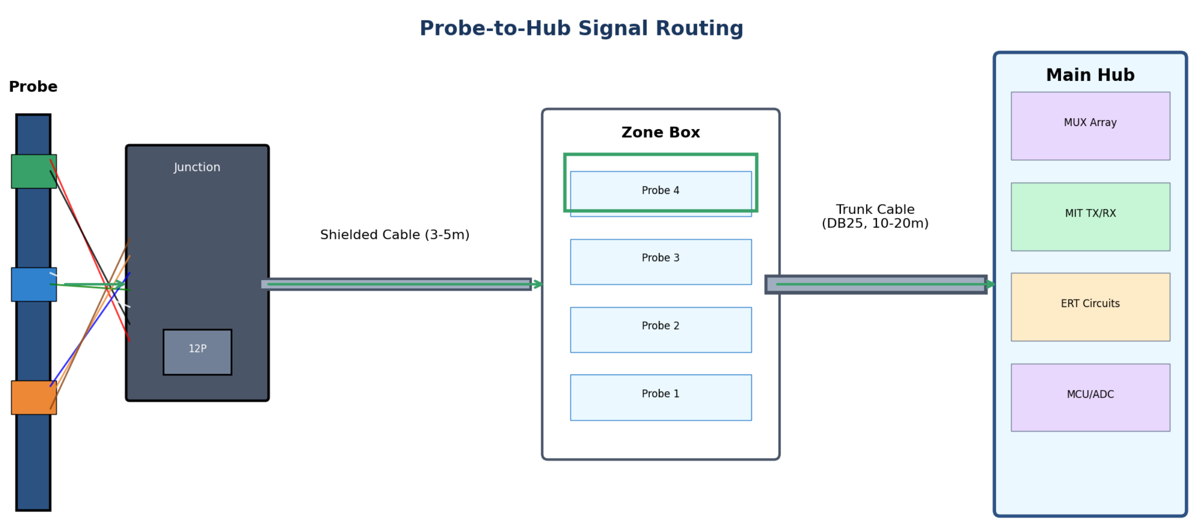


Figure 5. Complete signal routing from probe sensors through the junction box, zone box, and trunk cable to the main hub electronics. The hierarchical structure reduces wiring complexity.

7.5 Assembly Procedures

7.5.1 Preparation Steps

1. **Inspect All Parts:** Verify all printed parts are present and undamaged, no visible layer separation or cracks
2. **Prepare Workspace:** Clean, well-lit, well-ventilated area with protected work surface
3. **Test-Fit Parts (Dry Run):** Test thread engagement on all threaded parts, verify tube sections fit inserts, check O-ring sizing

7.5.2 Rod Segment Preparation

Cut fiberglass tubing to desired lengths (50 cm or 100 cm segments are standard). Use steady, even strokes with the hacksaw and rotate the tube to keep the cut square. After cutting, deburr the ends by removing fiberglass fibers with a file and sanding smooth with 400-grit sandpaper.

Rod Assembly Convention

- Rods have Male threads at bottom, Female at top
- Apply epoxy to flange of insert before installation
- Ensure shoulder sits flush against tube cut
- Allow 24 hours cure time before stressing threads

7.5.3 Field Assembly Sequence

Assembly proceeds from the bottom (tip) and works upward. Each joint uses thread sealant and an O-ring for waterproofing. The cable is threaded through each segment before connecting.

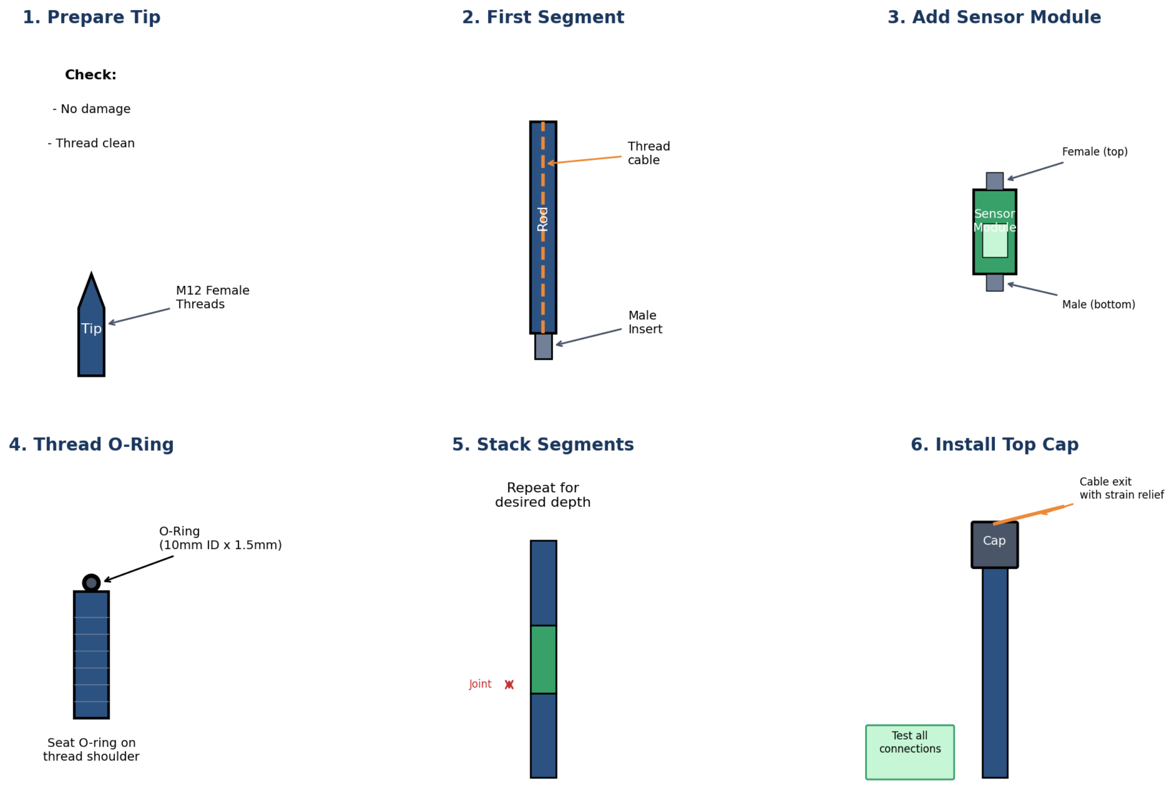


Figure 6. Six-step assembly sequence: (1) Prepare probe tip, (2) Thread cable through first segment, (3) Add sensor module, (4) Seat O-ring on thread shoulder, (5) Stack additional segments, (6) Install top cap with cable strain relief.

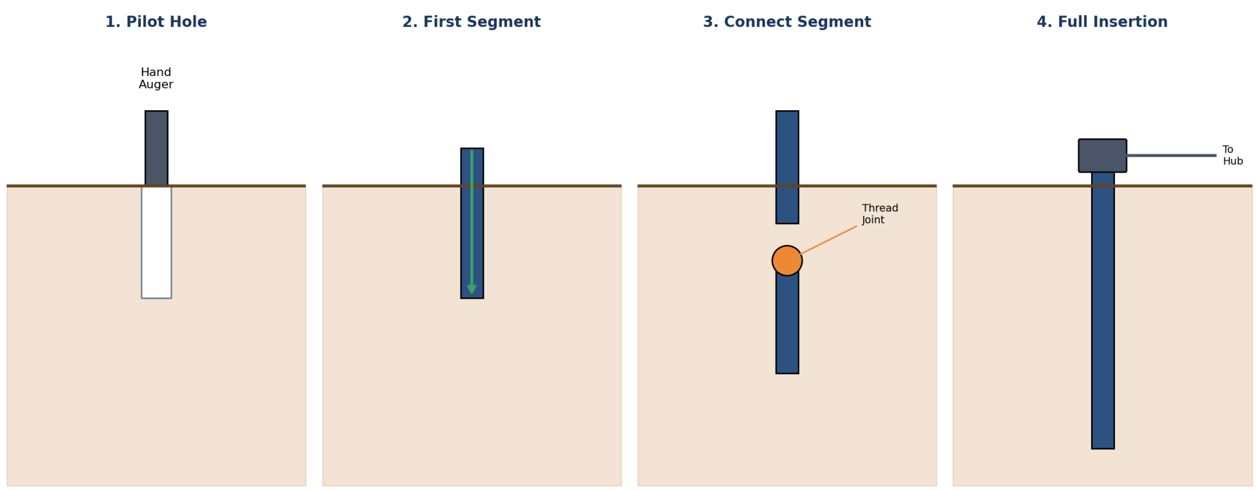


Figure 7. Probe insertion procedure showing pilot hole preparation, segment insertion, segment connection, and final installation with surface junction box.

7.6 Base Hub Assembly

The base hub houses all electronics in a weatherproof enclosure. The internal layout follows a stacked architecture for easy assembly and maintenance. The backplane PCB (160x120mm) contains all signal processing circuits organized into functional zones.

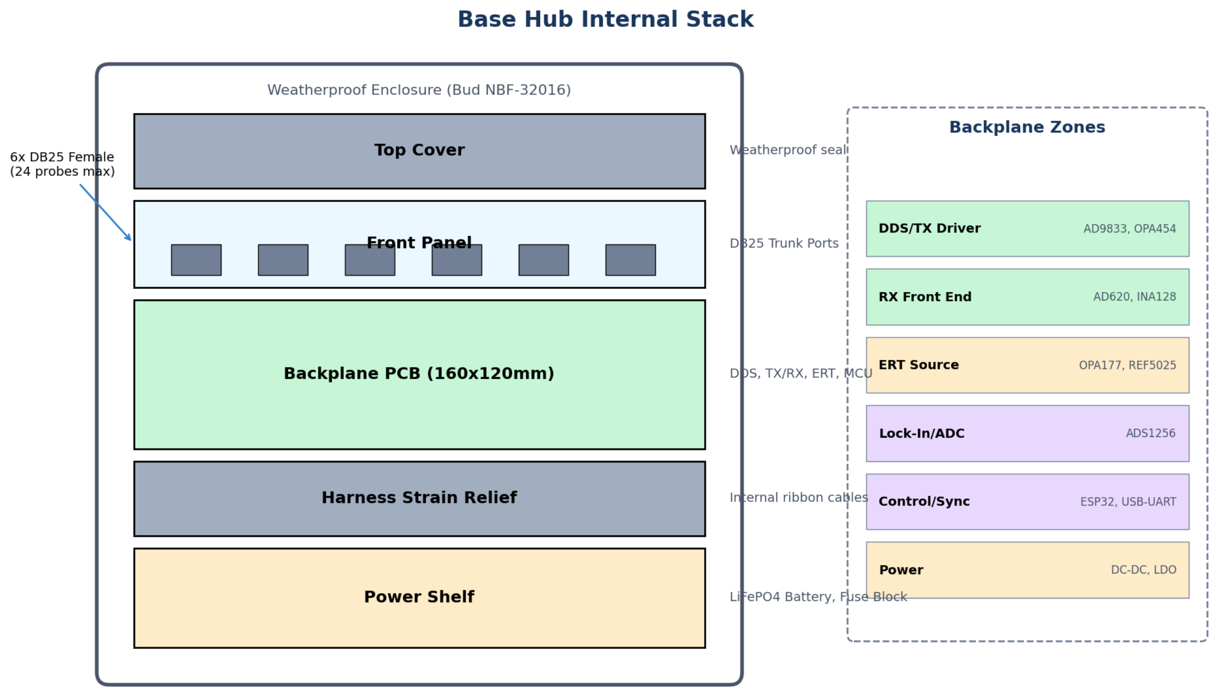


Figure 8. Base hub internal stack layout showing the layered architecture from power shelf at bottom to weatherproof cover at top. The backplane PCB contains all analog and digital circuits.

Zone	Function	Key Parts
DDS/TX Driver	Sweep generation	AD9833, OPA454
RX Front End	Signal conditioning	AD620, INA128
ERT Source	Current injection	OPA177, REF5025
Lock-In/ADC	Digitization	ADS1256
Control/Sync	Scheduling, logging	ESP32, USB-UART
Power	Regulation	DC-DC, LDO

Table 4. Backplane PCB functional zones

7.7 Quality Checks

7.7.1 During Assembly

- O-ring properly seated at each joint

- No gaps between components
- Threads fully engaged (hand tight + 1/4 turn)
- Cable has slack (not stretched at any joint)
- Joints are flush (smooth to touch)

7.7.2 After Complete Assembly

Mechanical Checks:

- Total length correct for intended depth
- All joints tight with no visible gaps
- Probe straight (no bends from misaligned joints)
- Cable secure at strain relief

Electrical Checks:

- All coil leads continuous (no opens) - verify with multimeter
- Coil inductance in spec (1-2 mH) - verify with LCR meter
- ERT ring isolation >1 M-ohm between all ring pairs
- No shorts between any conductors
- Shield continuity verified end-to-end

7.8 Troubleshooting

7.8.1 Thread Issues

Problem	Solution	Prevention
Threads too tight	Chase threads with tap/die	Print at correct tolerance, post-process
Threads too loose	Apply thread sealant (Teflon tape)	Check print settings, use proper tolerances
Threads stripped	Replace part	Hand-tight + 1/4 turn max, no over-tightening

Table 5. Thread issue troubleshooting guide

7.8.2 Electrical Issues

Problem	Solution	Check
Open circuit in coil	Check for broken wire, resolder	Wire may be damaged during assembly
Short between rings	Check for bridging, clean thoroughly	Conductive debris in gaps
Low coil Q factor	Rewrap coil more neatly	Shorted turns from damaged insulation

Table 6. Electrical issue troubleshooting guide

7.9 Assembly Tips

General Assembly Tips

- Work clean - Fiberglass dust and epoxy do not mix well
- Test often - Verify continuity at each stage
- Do not rush - Allow full cure time for epoxy (24 hours)
- Label everything - Mark probe ID on each segment
- Document - Record any deviations or issues

Epoxy Tips

- Mix thoroughly (2+ minutes of stirring)
- Apply thin coats - too much is messy and adds weight
- Work in well-ventilated area
- Clean up drips immediately with IPA
- Allow full cure before stressing joints

Thread Tips

- Use cutting oil with tap/die
- Back out tap every half-turn to clear chips
- If stuck, back out and clear - do not force
- Test fit with mating part before committing
- Apply light lubricant before final assembly

7.10 Post-Assembly

After complete assembly, proceed to the following sections for system verification:

1. Complete Testing Procedures (Section 8: Testing and Verification)
2. Complete Calibration Procedures (Section 9: Calibration)
3. Label and register probe in system database
4. Store properly in protective case until deployment

Important Reminders

- Allow epoxy to fully cure (24 hours) before field deployment
- Verify all electrical connections before sealing junction boxes
- Document probe configuration (sensor positions, coil specs) for each unit
- Store probes vertically to prevent cable stress at joints

Section 8: Testing and Verification

Quality Control Procedures for HIRT Probe Systems

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

8.1 Overview

This section provides comprehensive testing procedures and quality control checklists for HIRT probes before field deployment. All probes must pass these tests to ensure reliable field operation. The testing framework covers mechanical integrity, electrical functionality, subsystem performance, and system integration.

Testing Philosophy

- All tests must PASS for field deployment approval
- CONDITIONAL status requires documented workarounds and supervisor approval
- FAIL status requires repair, component replacement, and complete re-test
- Quantitative measurements recorded for traceability and trend analysis

8.2 Testing Workflow

The HIRT testing workflow follows a systematic progression from basic mechanical verification through complete system integration testing. Each stage must be completed successfully before proceeding to the next, ensuring that fundamental issues are identified and resolved before more complex testing begins.

8.2.1 Test Sequence

1. **Mechanical Testing** - Verify physical integrity of rod, probe head, ERT rings, and cables
2. **Electrical Testing** - Verify power supply, continuity, and communication interfaces
3. **MIT Subsystem Testing** - Verify coils, DDS, TX driver, RX chain, and coupling response
4. **ERT Subsystem Testing** - Verify ring isolation, contact resistance, and measurement chain
5. **System Integration Testing** - Verify complete system operation and data collection
6. **Environmental Testing** - Verify temperature stability and waterproofing (as applicable)
7. **QC Sign-off** - Final documentation review and deployment approval

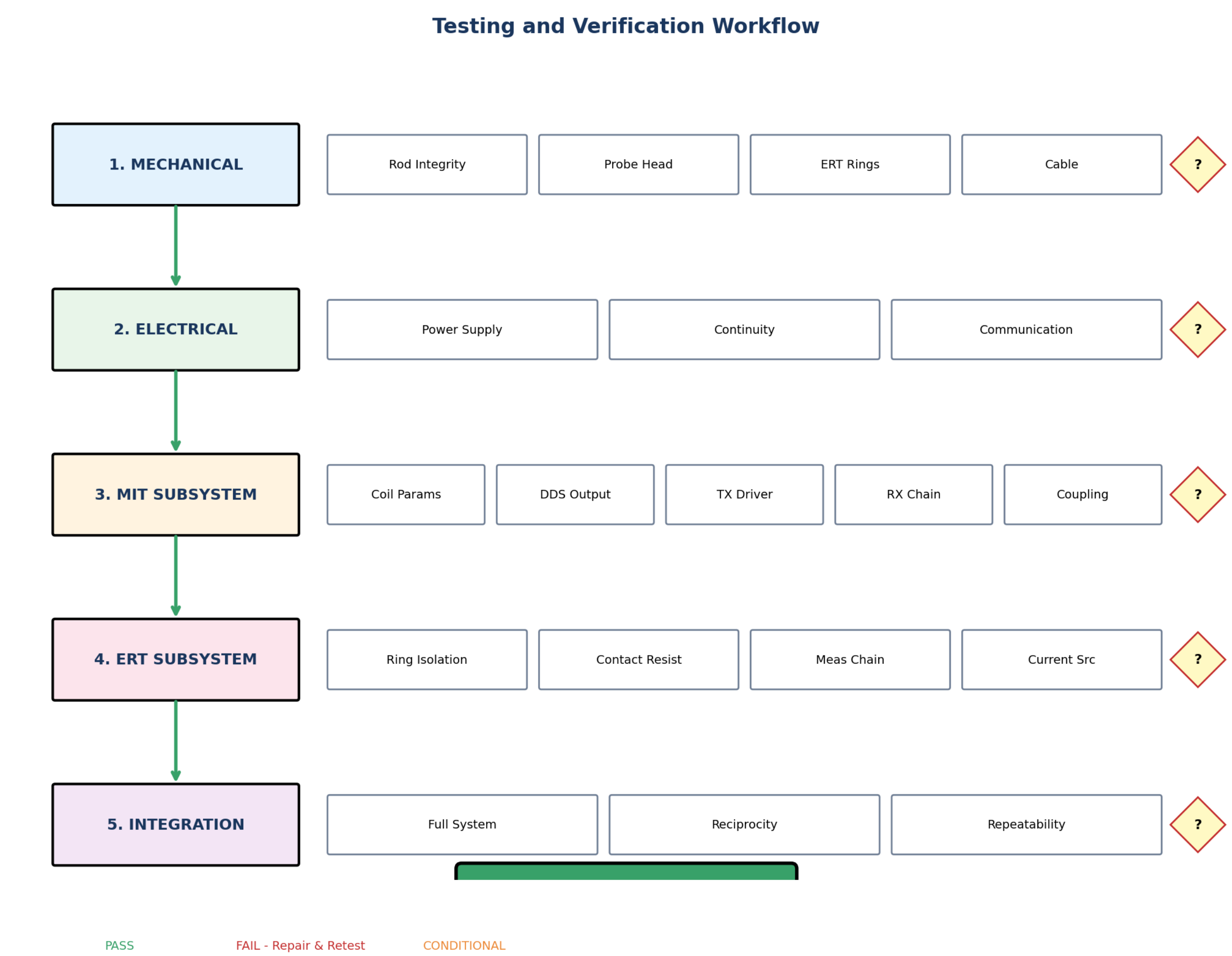


Figure 1. Complete testing and verification workflow showing test categories, individual tests within each category, and the sequential progression from mechanical testing through QC sign-off. Each decision point requires all tests within the category to pass before proceeding.

8.3 Pre-Testing Setup

8.3.1 Test Equipment Required

Equipment	Purpose	Minimum Specification
Power Supply	Probe power delivery	5V or 12V, current-limited to 2A
Digital Multimeter	Resistance, voltage, current	0.1% accuracy, 4.5 digit
LCR Meter	Coil inductance and Q factor	10 kHz test frequency, 0.1% accuracy
Oscilloscope	Signal verification	50 MHz bandwidth, 2-channel minimum
Function Generator	Signal injection testing	1 Hz - 100 kHz, sine/square
Base Hub	System-level testing	Complete calibrated unit

Table 1. Test equipment requirements for HIRT probe verification

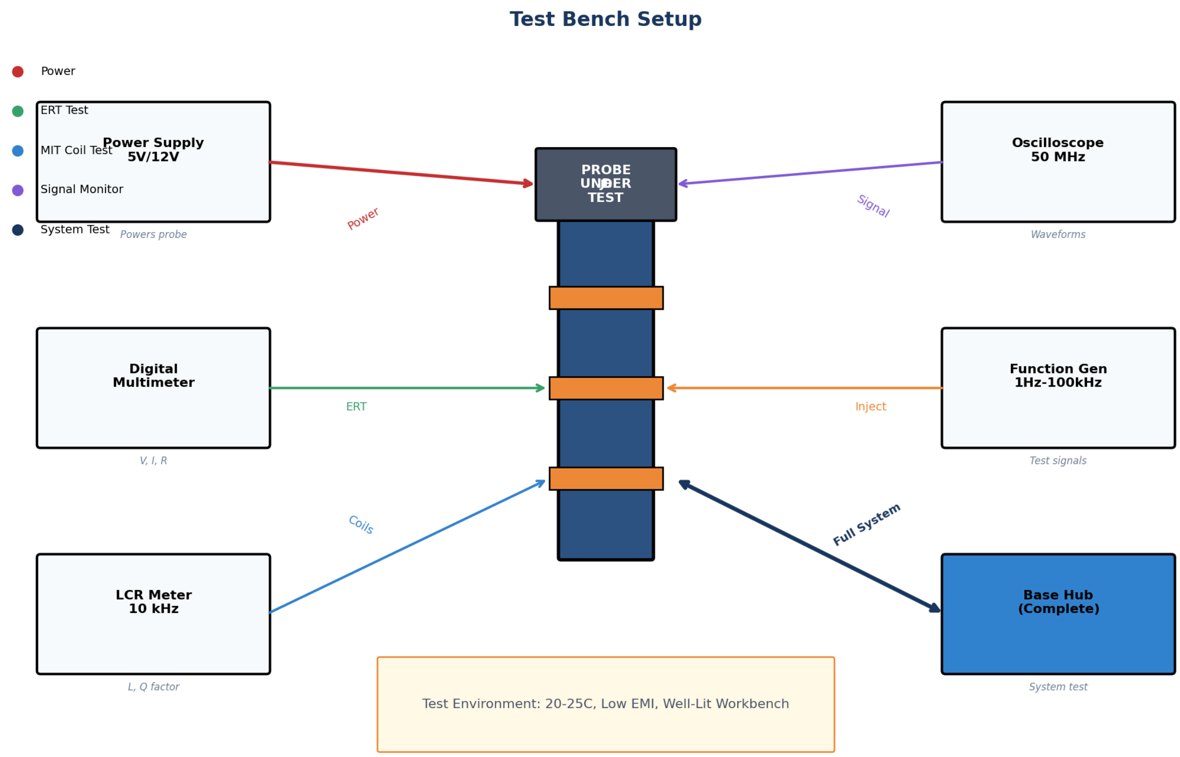


Figure 2. Test bench setup diagram showing the probe under test (center) connected to various test instruments. Power supply provides regulated DC power, DMM measures ERT parameters, LCR meter characterizes coils, oscilloscope monitors signals, function generator injects test waveforms, and base hub enables full system testing.

8.3.2 Test Environment Requirements

- Clean, well-lit workbench with adequate space for equipment and probe
- Temperature: 20-25 degrees C (controlled room temperature)
- Minimize EMI sources: move phones, radios, and switching power supplies away
- Follow electrical safety procedures: use current-limited supplies, proper grounding
- Prepare test log template, probe registry entry, and calibration sheet before starting

8.4 Mechanical Tests

8.4.1 Test M1: Rod Integrity

Purpose: Verify the probe rod is straight, undamaged, and properly assembled.

Procedure:

1. Inspect rod visually for cracks, bends, scratches, or other damage
2. Measure rod length using tape measure (should match specification +/-5 mm)
3. Roll rod on flat surface to check straightness - observe for wobble
4. Verify thread engagement on all joints (multi-section probes)
5. Perform gentle pull test on joints - no movement should occur

Pass Criteria: No visible damage, length within specification, rod straight, threads engaged properly, joints secure with no movement.

8.4.2 Test M2: Probe Head Integrity

Purpose: Verify the probe head (junction box) is properly sealed and assembled.

1. Inspect capsule for cracks, damage, or discoloration
2. Verify cap seal is properly seated with no gaps
3. Check cable gland seal - should be tight with no cable movement
4. Test attachment to rod - should be secure with no rotation
5. Shake gently to check for loose internal components

8.4.3 Test M3: ERT Ring Mounting

Purpose: Verify ERT electrode rings are properly mounted and positioned.

Ring	Position from Tip	Tolerance
Ring 1	0.5 m	+/- 2 cm
Ring 2	1.5 m	+/- 2 cm
Ring 3	2.5 m	+/- 2 cm

Table 2. ERT ring position specifications

8.4.4 Test M4: Cable Integrity

Visual inspection of cable for damage, kinks, or abrasion. Test continuity of all conductors end-to-end. Verify cable routing has no sharp bends that could damage insulation. Check strain relief at both ends. Gentle pull test to verify secure termination.

8.5 Electrical Tests

8.5.1 Test E1: Power Supply Verification

Purpose: Verify power input and regulation circuits function correctly.

Parameter	Target	Tolerance	Status
3.3V Rail	3.3V	+/- 0.1V	[ ] Pass [ ] Fail
5V Rail	5.0V	+/- 0.1V	[ ] Pass [ ] Fail
Current Draw	< spec	See datasheet	[ ] Pass [ ] Fail
Voltage Stability	Stable	No fluctuations	[ ] Pass [ ] Fail
Temperature	< 50C	No excessive heat	[ ] Pass [ ] Fail

Table 3. Power supply test criteria

8.5.2 Test E2: Continuity and Shorts

With power off, measure resistance between power and ground (should be >100 ohm). Check for shorts between all signal lines. Verify all connections are continuous end-to-end. Confirm shield connections are proper.

8.5.3 Test E3: Communication Interface

Connect probe to base hub. Send test command and verify response. Test data transfer with multiple packets. Check reliability over 100 transactions (must be >95% success rate).

8.6 MIT Subsystem Tests

8.6.1 Test MIT1: Coil Parameters

Parameter	TX Coil	RX Coil	Pass Criteria
Inductance	Measured: ___	Measured: ___	1-2 mH
Q Factor	Measured: ___	Measured: ___	> 20
DC Resistance	Measured: ___	Measured: ___	< 10 ohm
Coil Isolation	N/A	N/A	> 1 M ohm

Table 4. MIT coil parameter measurements

8.6.2 Test MIT2: DDS Output

Configure DDS for 10 kHz test frequency. Measure output with oscilloscope. Verify frequency accuracy is within +/-1%. Check output amplitude stability. Measure THD (target: <1%). Test at 2, 5, 10, 20, and 50 kHz.

8.6.3 Test MIT3: TX Driver Output

Measure DDS output before driver. Measure driver output after amplification. Calculate gain and compare to design specification (+/-10%). Verify no clipping or distortion. Test across frequency range.

8.6.4 Test MIT4: RX Chain Response

Inject known test signal into RX input. Measure signal at each amplification stage. Calculate gain at each stage. Verify total system gain matches design (+/-10%). Measure noise floor (target: <1% of full scale).

8.6.5 Test MIT5: Coupling Test

Set up two probes 1-3 m apart. Place aluminum calibration target between probes. Configure TX on one probe, RX on other. Measure amplitude and phase response. Remove target and establish baseline. Expected response with target: 10-50% amplitude drop, 5-30 degree phase lag.

8.7 ERT Subsystem Tests

8.7.1 Test ERT1: Ring Isolation

Measure resistance between adjacent rings (should be >1 M ohm). Measure each ring to ground and to probe rod body (all should be >1 M ohm). Repeat measurements after water exposure to verify sealing integrity.

8.7.2 Test ERT2: Contact Resistance

Insert probe into test medium (sand box with known resistivity). Inject test current (0.5-1 mA). Measure voltage between adjacent rings. Calculate contact resistance (target: <1000 ohm). Verify readings are stable with no drift.

8.7.3 Test ERT3: Measurement Chain

Apply known voltage to ERT input. Select each ring via multiplexer. Verify correct ring selection. Measure at amplifier output. Read ADC value and compare to expected (should be within +/-5%). Test all rings sequentially.

8.7.4 Test ERT4: Current Source

Connect to known test load resistance. Configure current levels: 0.5, 1.0, 1.5, 2.0 mA. Measure actual current at each setting. Verify accuracy is within +/-5%. Test stability over 1 minute at each level.

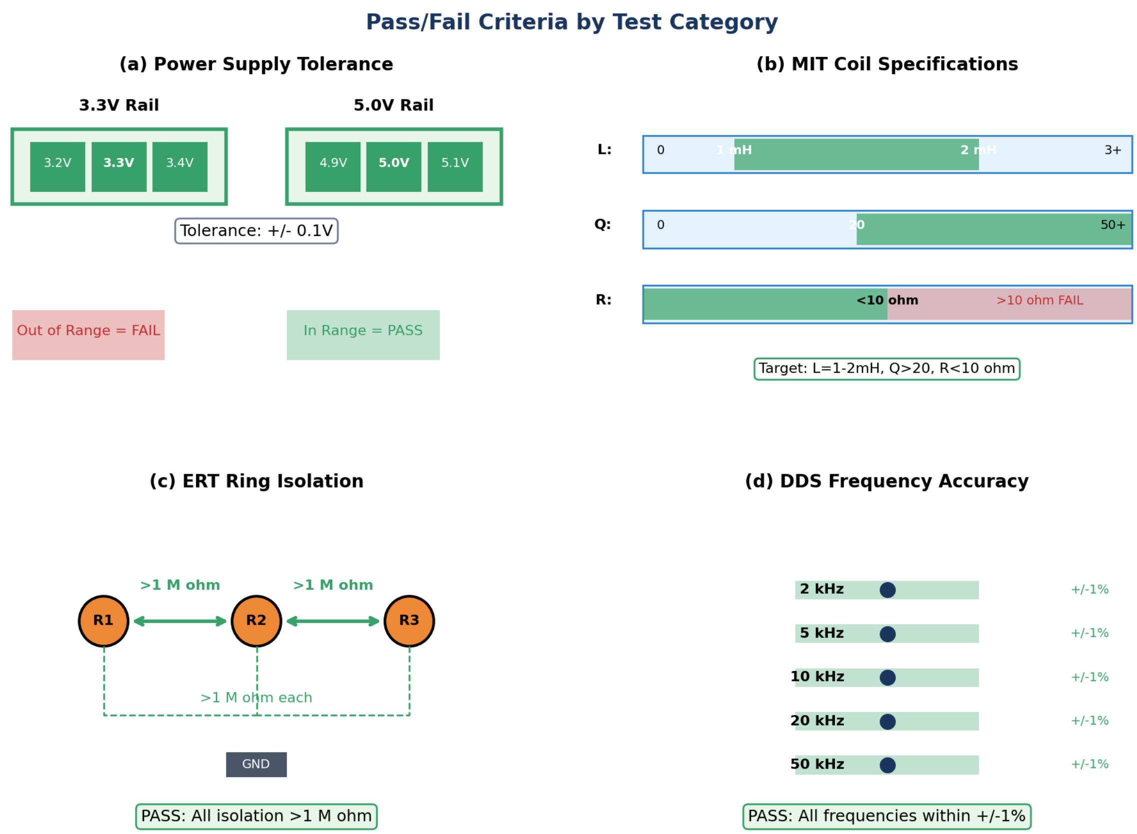


Figure 3. Visual representation of pass/fail criteria for key test parameters: (a) Power supply voltage tolerance bands showing the +/-0.1V acceptable range for 3.3V and 5V rails; (b) MIT coil specification ranges for inductance, Q factor, and DC resistance; (c) ERT ring isolation requirements showing minimum 1 M ohm between rings and to ground; (d) DDS frequency accuracy tolerance of +/-1% across all test frequencies.

8.8 System Integration Tests

8.8.1 Test INT1: Full System Test

Power on complete probe system. Verify communication with base hub. Test MIT measurement acquisition. Test ERT measurement acquisition. Verify data collection and storage. Test probe synchronization with other units.

8.8.2 Test INT2: Reciprocity Test

Set up two probes (A and B) at fixed separation. Measure A transmitting to B. Measure B transmitting to A. Compare results - should match within 5%. Repeat for multiple probe pairs to verify consistency.

8.8.3 Test INT3: Repeatability Test

Set up fixed test configuration. Take measurement. Wait 1 minute. Take same measurement. Repeat 5-10 times. Calculate mean and standard deviation. Pass criteria: standard deviation <5% of mean. No systematic drift over time.

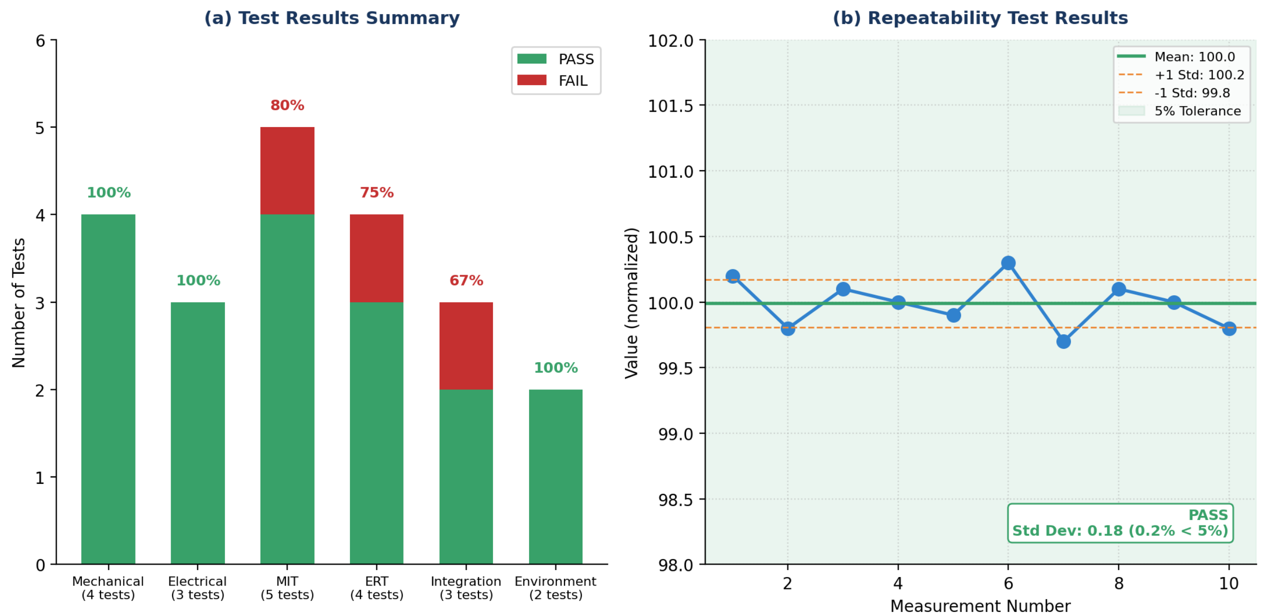


Figure 4. Test results recording template: (a) Summary bar chart showing pass/fail counts by test category with pass rate percentages; (b) Repeatability test trend chart showing individual measurements, mean value, standard deviation bands, and 5% tolerance envelope. This format enables rapid identification of problematic areas and provides documented evidence for QC sign-off.

8.9 Quantitative Validation Protocols

Beyond functional testing, rigorous quantitative validation is required to ensure the HIRT system meets scientific publication standards.

8.9.1 ERT Accuracy Validation (NIST-Traceable)

Connect precision metal-film resistors (0.1% tolerance) to probe electrode inputs. Test values: 100 ohm, 1 k ohm, 10 k ohm. Inject currents at 0.5, 1.0, 2.0 mA. Record 50 samples for each combination. Calculate Mean Absolute Percentage Error (MAPE).

*MAPE = (1/n) * SUM(|R_measured - R_true| / R_true) * 100%*

Target: MAPE < 1.0% across the dynamic range.

8.9.2 MIT Sensitivity Validation (Standard Loop)

Construct Standard Calibration Loop: single turn of 14 AWG copper wire, 10 cm diameter, shorted. Place loop coaxially with TX/RX pair at distances of 0.5 m, 1.0 m, 1.5 m. Measure change in mutual impedance at 10 kHz. Compare to analytical dipole-loop solution.

Target: Measurement within +/-10% of theoretical prediction.

8.9.3 Receiver Noise Characterization

Short RX inputs at Zone Hub. Record 10-second timeseries at 30 kSPS. Compute Power Spectral Density (PSD). Report input-referred noise in nV/sqrt(Hz) at 2, 10, 50 kHz.

Target: < 20 nV/sqrt(Hz) (comparable to commercial geophysical amplifiers).

8.10 QC Checklist Summary

QUALITY CONTROL REQUIREMENTS

- ALL mechanical checks must pass before electrical testing
- ALL electrical checks must pass before subsystem testing
- ALL subsystem checks must pass before integration testing
- FAIL on any critical test requires repair and COMPLETE re-test of that category
- CONDITIONAL status requires documented workarounds and supervisor approval

Category	Tests	Critical Items	Typical Time
Mechanical	M1-M4	Rod integrity, sealing	30 min
Electrical	E1-E3	Power rails, communication	30 min
MIT Subsystem	MIT1-MIT5	Coil params, coupling	60 min
ERT Subsystem	ERT1-ERT4	Ring isolation, accuracy	45 min
Integration	INT1-INT3	Full system, reciprocity	45 min
Environmental	ENV1-ENV2	Waterproofing	60 min

Table 5. QC test category summary

Overall Status Determination:

- **PASS:** All tests passed - probe approved for field deployment
- **CONDITIONAL:** Minor issues with documented workarounds - requires supervisor approval
- **FAIL:** Critical issues found - requires repair, component replacement, and re-test

8.11 Sign-Off and Documentation

Upon completion of all testing, the QC inspector must complete the sign-off form including probe ID, test date, inspector name, overall status, and any issues found with required actions. The completed test log, calibration sheet, and sign-off form must be filed with the probe registry before field deployment.

Documentation Requirements

- Completed test log with all measurements recorded
- Calibration sheet with coil parameters and baseline values
- Sign-off form with inspector signature and date
- Probe registry entry updated with test status and deployment approval

For calibration procedures, see Section 9: Calibration. For troubleshooting guidance when tests fail, see Section 13: Troubleshooting.

Section 9: Calibration

MIT and ERT Calibration Procedures for Field-Ready Probes

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

9.1 Overview

This section provides detailed calibration procedures for HIRT probes before field deployment. Calibration ensures accurate and consistent measurements across all probes in the array. The dual-channel nature of HIRT (MIT and ERT) requires calibration of both subsystems, along with system-level verification to ensure the complete measurement chain performs within specification.

Proper calibration is essential for scientific data quality. Without it, probe-to-probe variations can introduce systematic errors that compromise tomographic reconstruction. The procedures outlined here establish traceability from individual components through to array-level cross-calibration.

9.2 Calibration Principles

Why Calibrate?

1. **Probe-to-probe consistency** - Ensure all probes give comparable readings under identical conditions
2. **Accuracy** - Relate measurements to physical units (mH, ohms, volts)
3. **Drift compensation** - Account for component aging and environmental effects
4. **Quality assurance** - Verify proper assembly and function before deployment

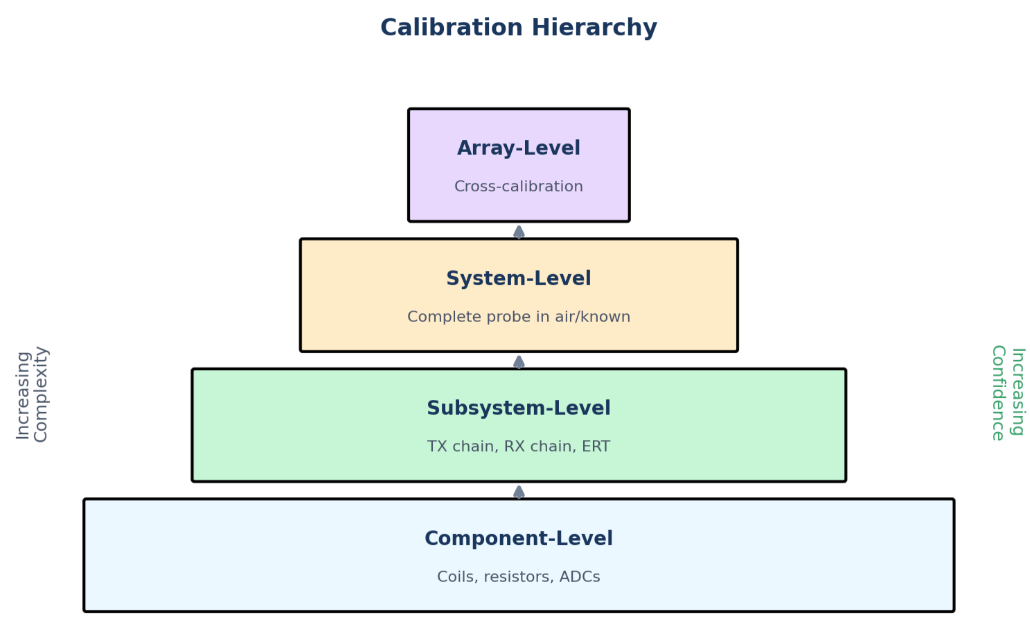


Figure 1. Calibration hierarchy showing the progression from component-level measurements through array-level cross-calibration. Each level builds upon the previous, increasing overall system confidence.

Key Parameters and Tolerances

Parameter	Target	Tolerance
Coil Inductance	1-2 mH	+/-10%
Coil Q Factor	>20	Minimum
DDS Frequency	Commanded	+/-1%
TX Amplitude	Design spec	+/-10%
RX Gain	Design spec	+/-10%
ERT Current	Commanded	+/-5%
Reciprocity	A->B = B->A	+/-5%

Table 1. Calibration parameters and acceptance tolerances

9.3 Calibration Workflow

The calibration workflow proceeds through three main phases: MIT calibration (air baseline, known resistor test, frequency sweep), ERT calibration (ring isolation, contact resistance, current source verification), and target response characterization (metal target tests, distance sweeps, lookup table generation).

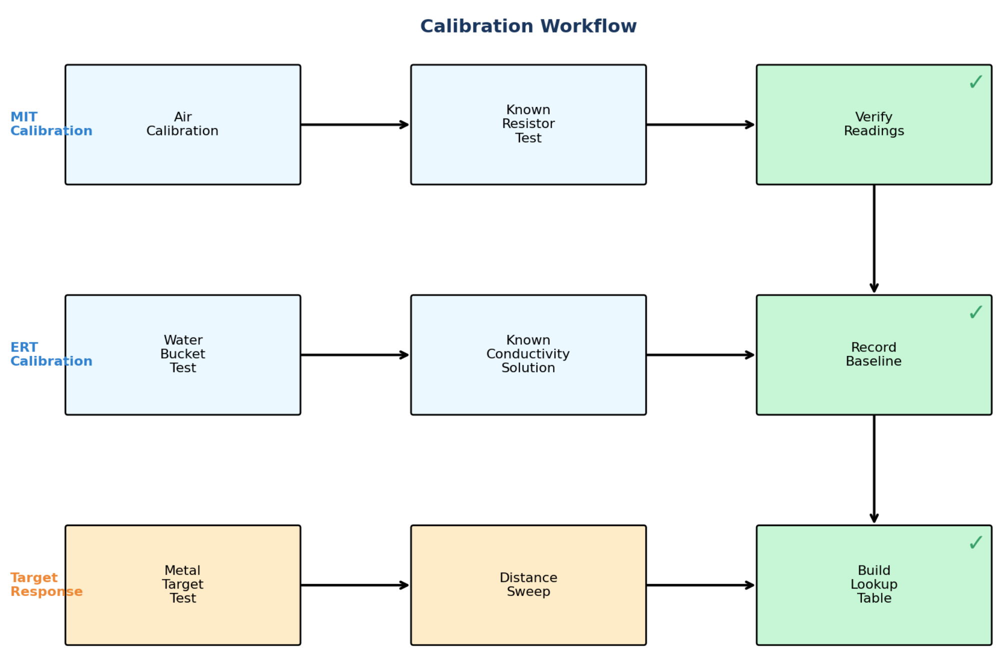


Figure 2. Complete calibration workflow showing the three-phase approach: MIT calibration (blue), ERT calibration (green), and target response characterization (orange). Checkmarks indicate verification points where data is recorded.

9.4 Required Equipment

Equipment	Purpose	Notes
LCR Meter	Coil measurements	Set to 10 kHz
Oscilloscope	Signal verification	50 MHz minimum
Multimeter	V/I/R measurements	6-digit preferred
Function Generator	Signal injection	1 Hz - 100 kHz
Known Test Targets	Coupling verification	Al plate, steel bar
Test Medium	ERT testing	Sand box, known resistivity
Reference Probe	Cross-calibration	If available

Table 2. Required calibration equipment

Environment Requirements

- Temperature: 20-25C (stable, within +/-2C during calibration)
- EMI: Minimize interference sources (turn off nearby equipment, use shielded area)
- Warm-up time: Allow 15-30 minutes for equipment stabilization
- Humidity: <80% RH to prevent condensation on probe surfaces

9.5 Air Calibration Setup

Air calibration establishes the baseline response of the probe when isolated from all external influences. The probe is suspended on a non-metallic stand (wood, PVC, or fiberglass) at least 1 meter from any metal objects. This measurement provides the 'zero' reference for subsequent target detection.

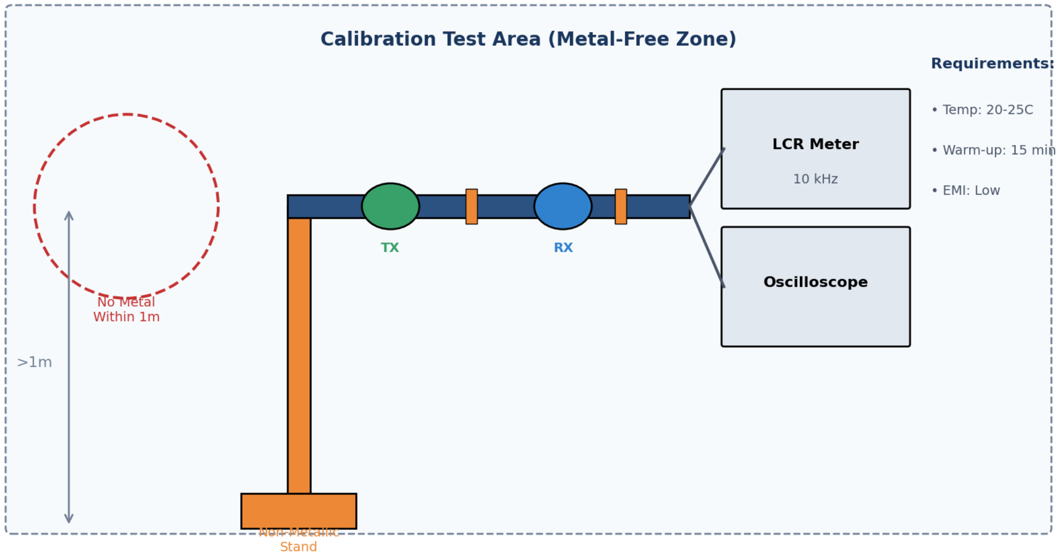


Figure 3. Air calibration test setup showing probe suspended on non-metallic stand with test equipment connections. The 1-meter exclusion zone ensures no spurious coupling from nearby metal objects.

9.6 Coil Calibration Procedures

TX Coil Inductance

1. Connect LCR meter to TX coil leads (ensure proper polarity)
2. Set measurement frequency to 10 kHz
3. Measure inductance (L) and record in mH
4. Compare to specification: target 1-2 mH, tolerance +/-10%
5. Record Pass/Fail status on calibration sheet

TX Coil Q Factor

1. Using same LCR meter setup as inductance measurement
2. Measure Q factor directly if meter supports it
3. Alternatively, calculate: Q = (2 x pi x f x L) / R
4. Target: Q > 20 (minimum acceptable value)
5. Low Q indicates winding issues or core problems

RX Coil Parameters

Repeat the inductance and Q factor measurements for the RX coil. The RX coil specifications should match the TX coil within tolerance to ensure balanced coupling characteristics. Record all measurements on the calibration sheet.

9.7 TX Chain Calibration

DDS Frequency Accuracy

Verify the DDS (Direct Digital Synthesis) generates correct frequencies across the operating range. Test at: 2, 5, 10, 20, and 50 kHz. Measure each commanded frequency with an oscilloscope and calculate frequency error.

Error (%) = (f_actual - f_commanded) / f_commanded x 100

Expected accuracy: +/-1% or better. Larger errors indicate DDS programming issues or clock reference problems.

TX Output Amplitude

- DDS output: ~0.6 V RMS typical (before driver stage)
- Driver output: 1-5 V RMS (design dependent)
- Gain should be 2-5x across frequency range
- Check for flat frequency response (+/-1 dB)

9.8 RX Chain Calibration

RX Chain Gain

Verify RX amplification chain gain by injecting a known test signal at the RX input and measuring output at each stage. A typical test signal is 1 mV at 10 kHz. Measure at preamp output, instrumentation amplifier output, and ADC input. Calculate gain at each stage and total system gain.

RX Noise Floor

1. Place probe in quiet environment (away from metal objects)
2. Apply no input signal (or short input terminals)
3. Measure output noise amplitude over 10-second window
4. Record multiple measurements and calculate standard deviation
5. Target: Noise floor < 1% of full scale

9.9 Known-Target Test Setup

The known-target test verifies that the complete MIT system detects conductive targets with the expected amplitude and phase response. Two probes are set up 1-3 meters apart with a known target (aluminum plate or steel bar) placed between them. This test validates both the detection sensitivity and the multi-frequency response characteristics.

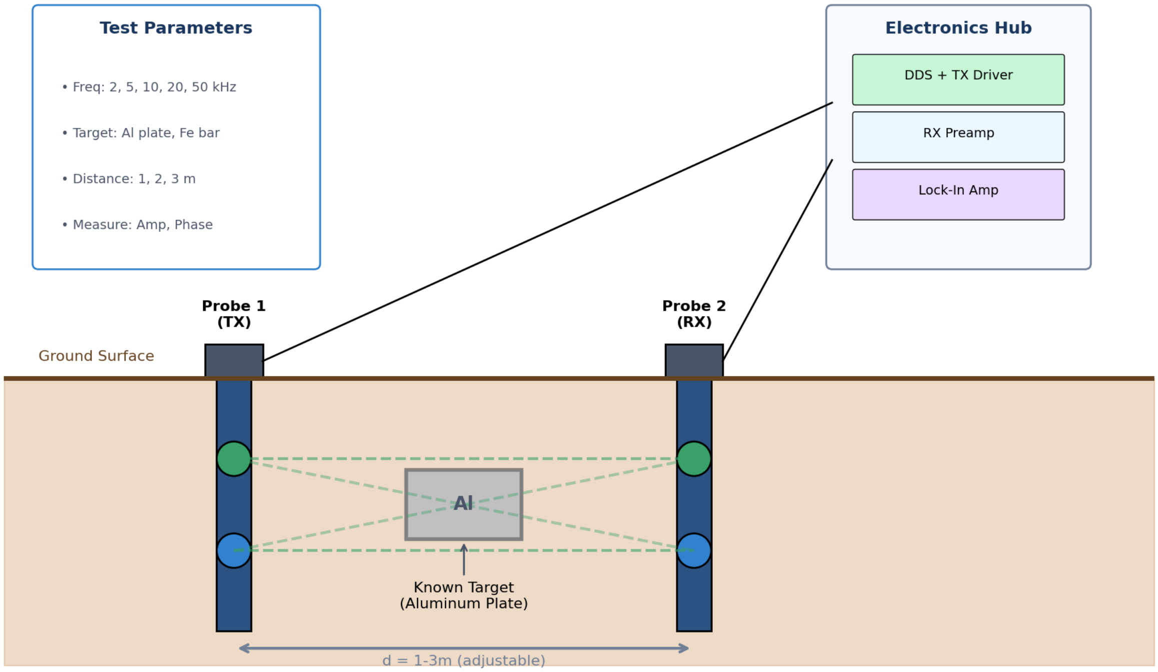


Figure 4. Known-target test configuration with two probes and calibration target. The aluminum plate provides a non-magnetic conductive target, allowing verification of eddy current detection without ferrous interference.

Expected Results

- Amplitude reduction: 10-50% depending on target size and distance
- Phase lag: 5-30 degrees depending on frequency and target conductivity
- Lower frequencies show deeper sensitivity (skin depth effect)
- Response should scale predictably with target distance

9.10 Calibration Data Analysis

Calibration data should be plotted to verify system behavior matches expected models. The amplitude response shows the normalized signal strength versus frequency for both baseline (air) and with-target conditions. The phase response shows the phase angle change introduced by the target. Both measurements should fall within specified tolerances.

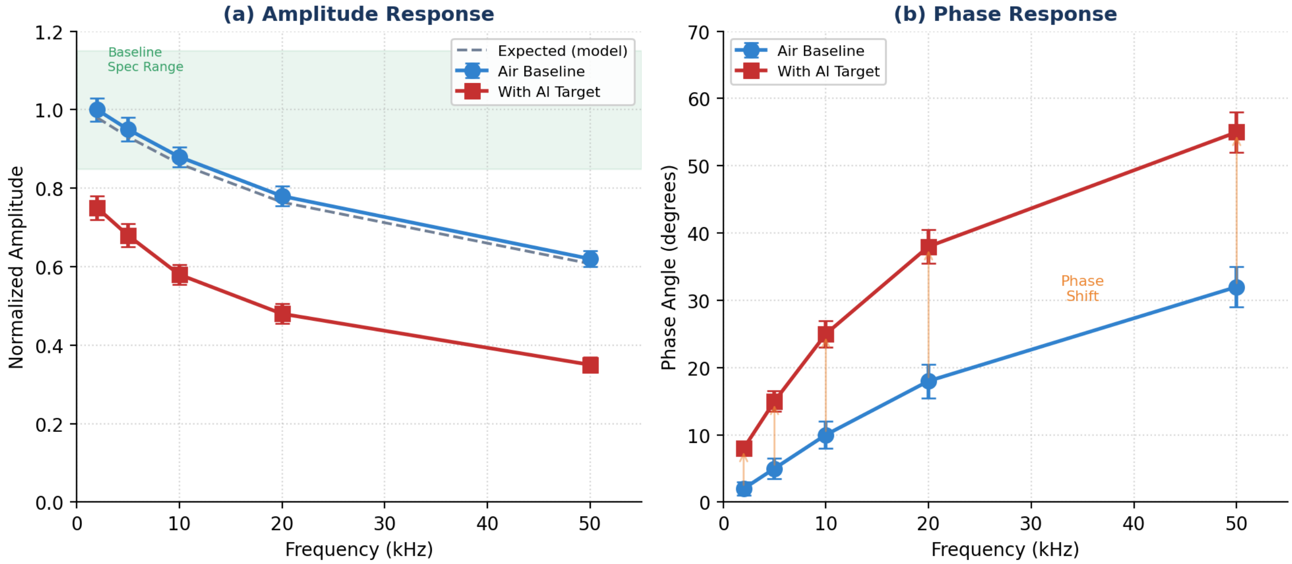


Figure 5. Representative calibration data showing (a) amplitude response and (b) phase response across the MIT operating frequency range. Error bars indicate measurement uncertainty. The phase shift between baseline and with-target conditions provides target characterization information.

9.11 ERT Calibration

Ring Isolation Verification

Verify electrical isolation between ERT rings to ensure independent measurements. Measure resistance between all ring pairs, between rings and ground, and between rings and the probe rod. All measurements should exceed 1 M-ohm. Lower values indicate contamination or insulation failure.

Current Source Calibration

1. Connect current source to test load (1 k-ohm precision resistor)
2. Set commanded current level (start at 1 mA)
3. Measure actual current with calibrated multimeter
4. Calculate calibration factor: Cal = I_actual / I_commanded
5. Test across full range: 0.5, 1.0, 1.5, 2.0 mA
6. Record all values and average calibration factor

9.12 Error Analysis and Uncertainty Budget

Scientific data reporting requires characterizing not just the measured value, but its uncertainty. The HIRT system has both systematic errors (consistent offsets that can be removed via calibration) and random errors (unpredictable fluctuations reduced by averaging).

Source	Type	Magnitude	Distribution
Reference Resistor	Systematic	0.1%	Rectangular
ADC Quantization	Random	< 1 uV	Uniform
Thermal Drift	Systematic	50 ppm/C	Linear
Probe Geometry	Random	+/- 1 cm	Normal
Combined Uncertainty	Mixed	~1-2%	(k=2)

Table 3. Typical uncertainty budget for HIRT measurements

All final data products should be reported with 95% confidence intervals (k=2):

Measurement = X +/- 2 sigma

9.13 Field Quick-Check Procedure

Before each field deployment, perform these abbreviated checks to verify system readiness. This procedure takes approximately 15-30 minutes and can identify common issues before they affect data collection.

Pre-Deployment Quick Check

- Visual inspection: No visible damage, all connections secure
- Power check: System powers on, LEDs functioning, communication established
- Coil quick test: TX/RX connected (~1-2 mH), Q factor reasonable (>20)
- ERT quick test: Rings isolated (>1 M-ohm), no shorts to ground
- Coupling verification: Wave hand near coil and observe response

9.14 Recalibration Schedule

Trigger	Action
Before each field deployment	Quick check
After repairs or modifications	Full calibration
If measurements become inconsistent	Full calibration
Every 6 months minimum	Full calibration
After environmental exposure	Full calibration

Table 4. Recalibration schedule triggers and actions

Calibration is considered valid if: all measurements are within specifications, no repairs or modifications have been made since calibration, system performance remains consistent, and the calibration validity period has not expired (typically 6 months).

9.15 Documentation Requirements

Maintain complete calibration records for all probes in the system. Records should include probe identification, calibration date, calibrator name, all measured values with units, pass/fail status for each parameter, and recalibration due date. Store records in both digital and printed formats.

Calibration Record Retention

- All probes must have current calibration records
- Records must be available during field operations
- Out-of-tolerance conditions must be documented
- Probes failing calibration must not be deployed

Section 10: Field Operations

HIRT Field Deployment Procedures and Survey Protocols

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

10.1 Overview

This section provides comprehensive procedures for deploying and operating the HIRT (Hybrid Inductive-Resistivity Tomography) system in the field, from pre-deployment planning through data backup. The HIRT system combines Magnetic Induction Tomography (MIT) and Electrical Resistivity Tomography (ERT) measurements using a modular array of subsurface probes to achieve high-resolution imaging of buried targets.

10.2 Pre-Deployment Planning

Site Assessment (Day Before)

Thorough preparation is critical to successful field operations. Before deployment, conduct a comprehensive site assessment covering the following aspects:

1. **Review site conditions:** Evaluate soil type and moisture levels, identify presence of utilities or obstructions, and establish access routes and staging areas.
2. **Check equipment:** Verify all probes are tested and calibrated, ensure base hub battery is charged (>80%), verify cable continuity, and confirm data logger/tablet is configured.
3. **Verify permits and permissions:** Confirm site access authorization, excavation permits (if required), and archaeological survey approval.

Equipment Checklist

Category	Item	Quantity	Notes
Essential	Probes (tested)	20-24	Full functional test
Essential	Base hub/control unit	1	Battery >80%
Essential	Connection cables	3-5 m each	Verified continuity
Essential	Fiberglass survey stakes	As needed	For marking
Essential	Measuring tape	30 m min	Metric markings
Essential	Field tablet/laptop	1	Configured with software
Essential	Tool kit	1	Wrenches, screwdrivers, multimeter
Optional	GPS unit	1	Sub-meter accuracy preferred
Optional	Weather station	1	Temperature, humidity
Optional	Backup battery	1	12V compatible

Table 1. Field equipment checklist for HIRT deployment

10.3 Site Assessment and Grid Design

Grid design is fundamental to survey success. The grid geometry determines spatial resolution, depth sensitivity, and survey efficiency. Standard configurations are provided below, with adjustments based on site-specific requirements.

Configuration	Grid Size	Spacing	Probes	Application
Standard	10 x 10 m	2.0 m	20-24	General surveys
Small	8 x 8 m	1.5 m	12-16	Woodland/confined areas
Large	15 x 15 m	2.5 m	30-36	Crater sites, open areas
High Resolution	6 x 6 m	1.0 m	36	Detailed anomaly mapping

Table 2. Standard grid configurations for different survey scenarios

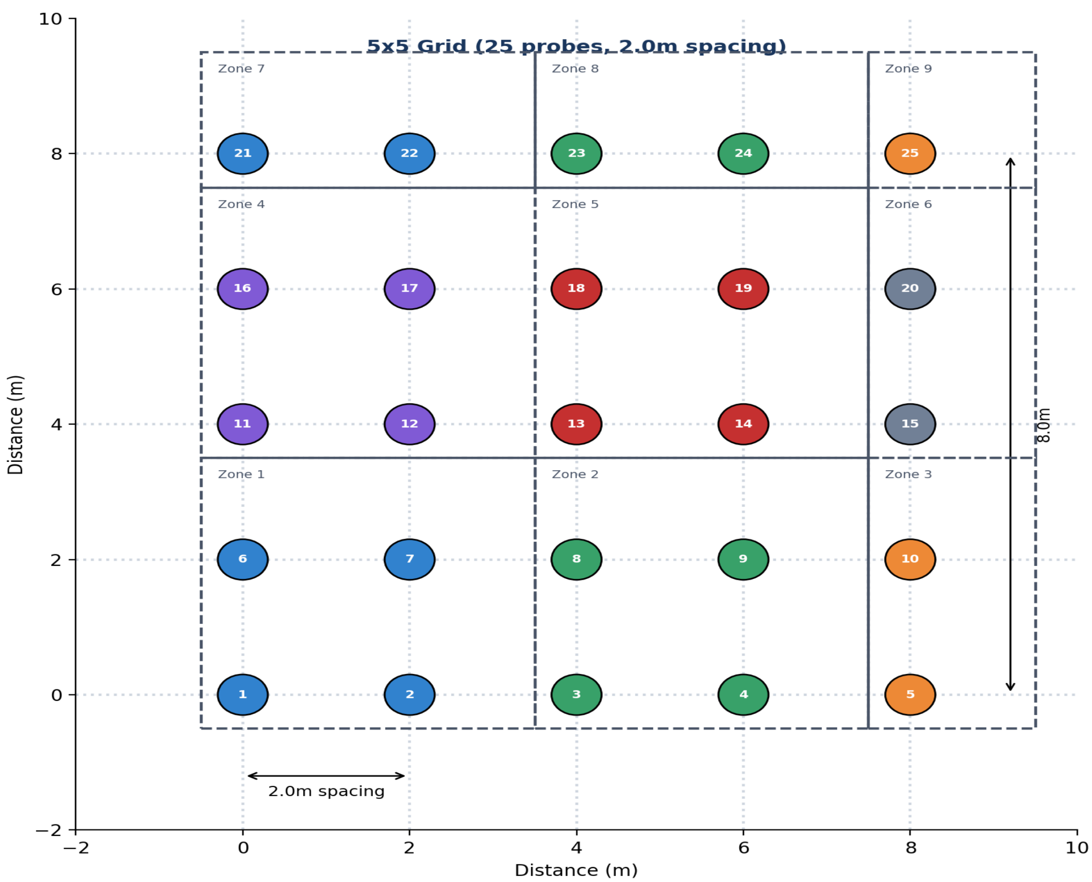


Figure 1. Standard 10x10 m grid layout with 2 m probe spacing showing zone groupings for sequential deployment. Probes are numbered 1-25 in row-major order.

Grid Setup Steps

1. **Establish baseline:** Set reference point (0,0) with survey stake, align baseline with site grid (N-S or as specified), and mark corners with bright flags.
2. **Mark probe positions:** Measure spacing intervals along baseline, extend perpendicular rows, and mark each position with small stake or flag.

3. **Verify geometry:** Cross-measure diagonals (should match within 5 cm) and record any deviations in field notes.

10.4 Probe Installation

Proper probe installation is critical for obtaining quality data. Insertion depth and technique vary with soil conditions and target depth requirements.

Scenario	Target Depth	Insertion Depth	Notes
Woodland survey	1-2 m	1.5 m	Standard for shallow targets
Crater survey	2-4 m	3.0 m	Extended depth for crater fill
Reconnaissance	0.5-1 m	1.0 m	Rapid screening mode

Table 3. Recommended insertion depths by survey scenario

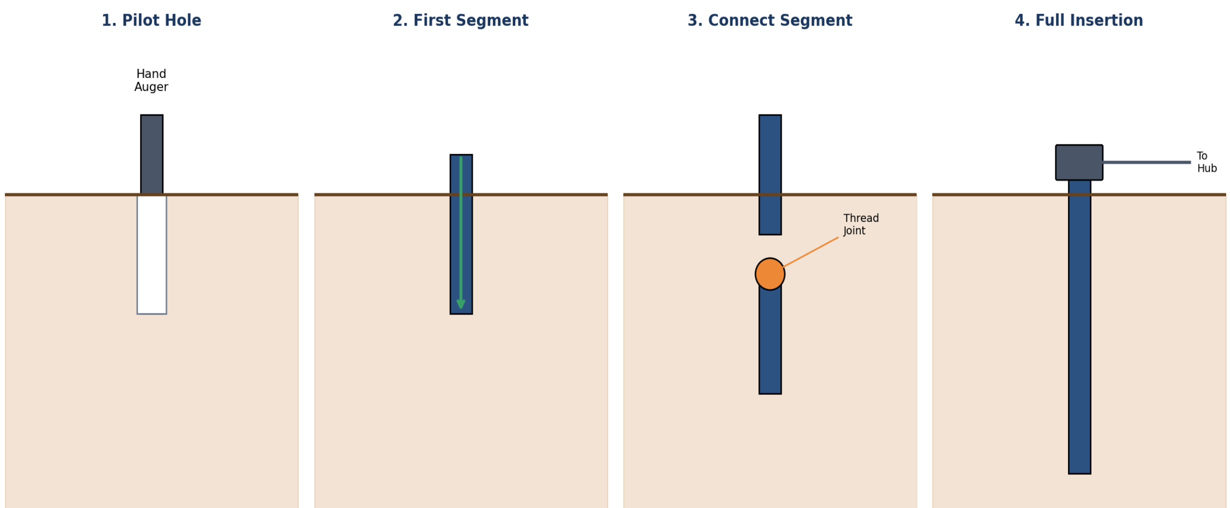


Figure 2. Probe insertion procedure showing the four-step process: (1) pilot hole creation with hand auger, (2) first segment insertion, (3) segment connection at thread joint, and (4) completed installation with junction box and cable routing.

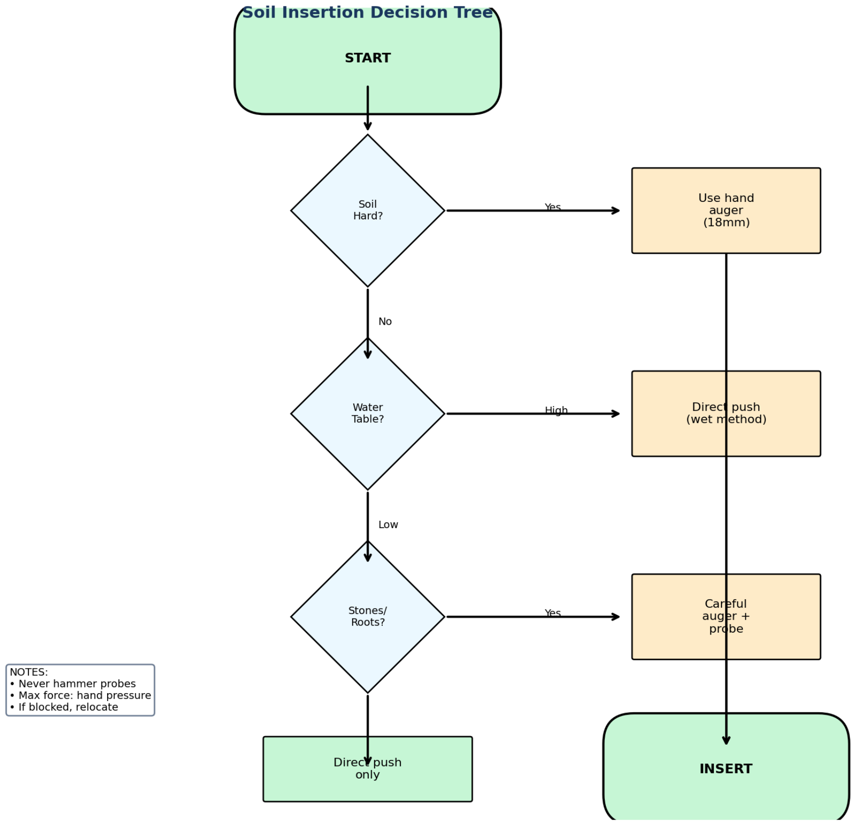


Figure 3. Soil type insertion decision tree. The procedure adapts based on soil hardness, water table depth, and presence of obstructions. Key principle: never hammer probes; use maximum hand pressure only.

Insertion Methods by Soil Type

Sandy/Loose Soil

- May push probe directly without pilot hole
- Use water jet if available for deeper insertion
- Watch for collapse of hole walls during insertion

Clay/Compact Soil

- Pre-drill pilot hole using 18 mm hand auger
- May need to enlarge hole slightly for probe diameter
- Allow settling time (5-10 min) before measurement

Rocky/Mixed Soil

- Use auger with care to avoid damage
- Note rock contact locations in field log
- May need to relocate probe position slightly

Cable Routing Guidelines

- Route cables radially from base hub placed at grid center or edge
- Route cables along grid lines to avoid tangling
- Use cable clips or ties to secure at 1 m intervals
- Leave 0.5 m slack at each probe connection for strain relief

10.5 System Setup and Power-Up

After probe installation, systematic setup and verification ensures reliable data acquisition. Follow the power-up sequence carefully to avoid equipment damage and verify all connections before beginning measurements.

Power-Up Sequence

1. **Connect all cables:** Verify each probe is connected to the base hub, check cable routing for kinks or tension points.
2. **Power on base hub:** Turn main power switch ON, wait for initialization (10-15 seconds), and verify power LED is solid green.
3. **Verify probe communication:** Run diagnostic scan, verify all probes report status, and note any non-responsive probes for troubleshooting.
4. **Initialize measurement system:** Start field software, load site configuration, and verify probe array geometry matches field deployment.

10.6 MIT Measurement Protocol

Magnetic Induction Tomography measurements detect conductive anomalies through electromagnetic coupling. Each probe sequentially transmits while all others receive, building a complete response matrix at multiple frequencies.

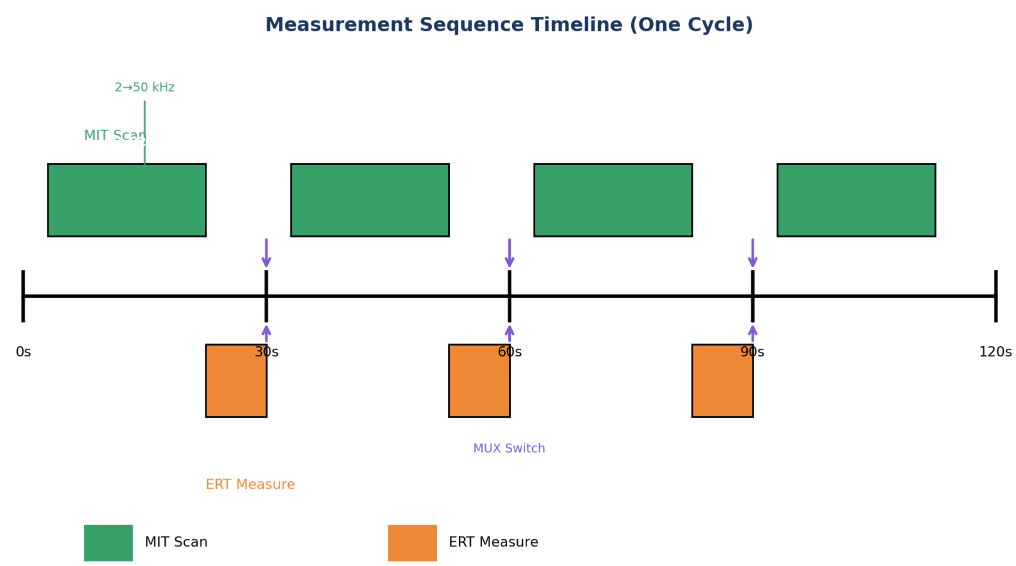


Figure 4. Measurement sequence timeline showing interleaved MIT scanning and ERT measurement cycles. MIT scans sweep through frequencies (2-50 kHz) while ERT measurements occur during multiplexer switching intervals.

Frequency Selection

Frequency	Penetration	Primary Use
2 kHz	Deep (3-4 m)	Deep target detection, high conductivity
5 kHz	Medium-deep	General subsurface mapping
10 kHz	Medium	Balanced depth/resolution
20 kHz	Shallow-medium	Enhanced resolution
50 kHz	Shallow (<1 m)	Near-surface detail, small targets

Table 4. MIT frequency selection guide for different survey objectives

Timing

- Full matrix measurement: all TX-RX pairs at single frequency (3-5 minutes)
- Multi-frequency sweep: complete matrix at all frequencies (30-45 minutes)
- Typical survey cycle: 10-15 minutes per complete scan at primary frequency

10.7 ERT Measurement Protocol

Electrical Resistivity Tomography measurements inject DC current across probe pairs while measuring voltage at all other electrodes. Multiple injection patterns provide complementary sensitivity for robust inversion.

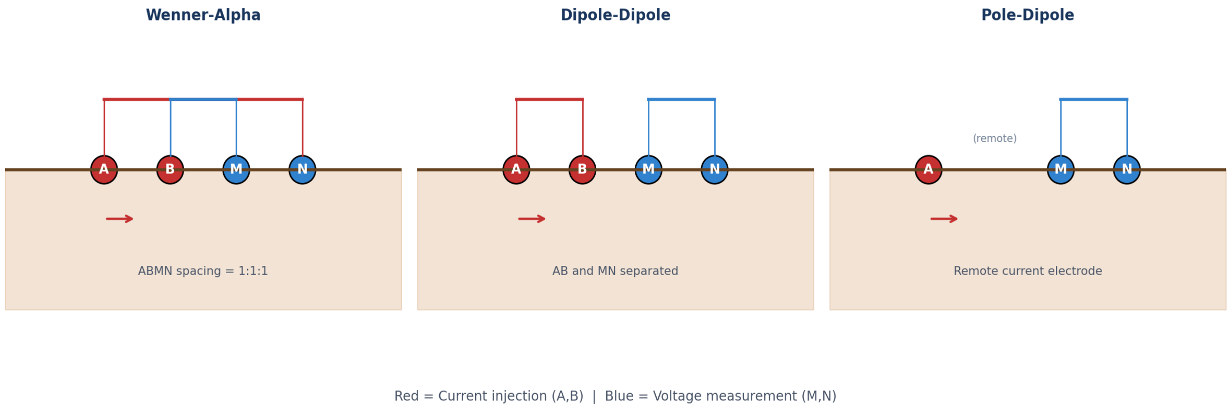


Figure 5. ERT injection pattern options. (a) Wenner-Alpha: symmetric ABMN spacing for uniform sensitivity. (b) Dipole-Dipole: separated current and voltage dipoles for lateral resolution. (c) Pole-Dipole: remote current electrode for deep penetration.

ERT Configuration Parameters

Parameter	Standard Value	Range	Notes
Current level	1.0 mA	0.5-2.0 mA	Adjust for noise floor
Integration time	2 s	1-5 s	Longer for noisy sites
Polarity reversal	Every 1 s	0.5-2 s	Reduces electrode polarization
Stacking	4 cycles	2-8	More for weak signals

Table 5. ERT measurement configuration parameters

10.8 "Set Once, Measure Many" Workflow

The HIRT operational philosophy emphasizes thorough probe placement followed by comprehensive measurement. This approach maximizes data quality and enables redundancy checks while minimizing handling of deployed equipment.

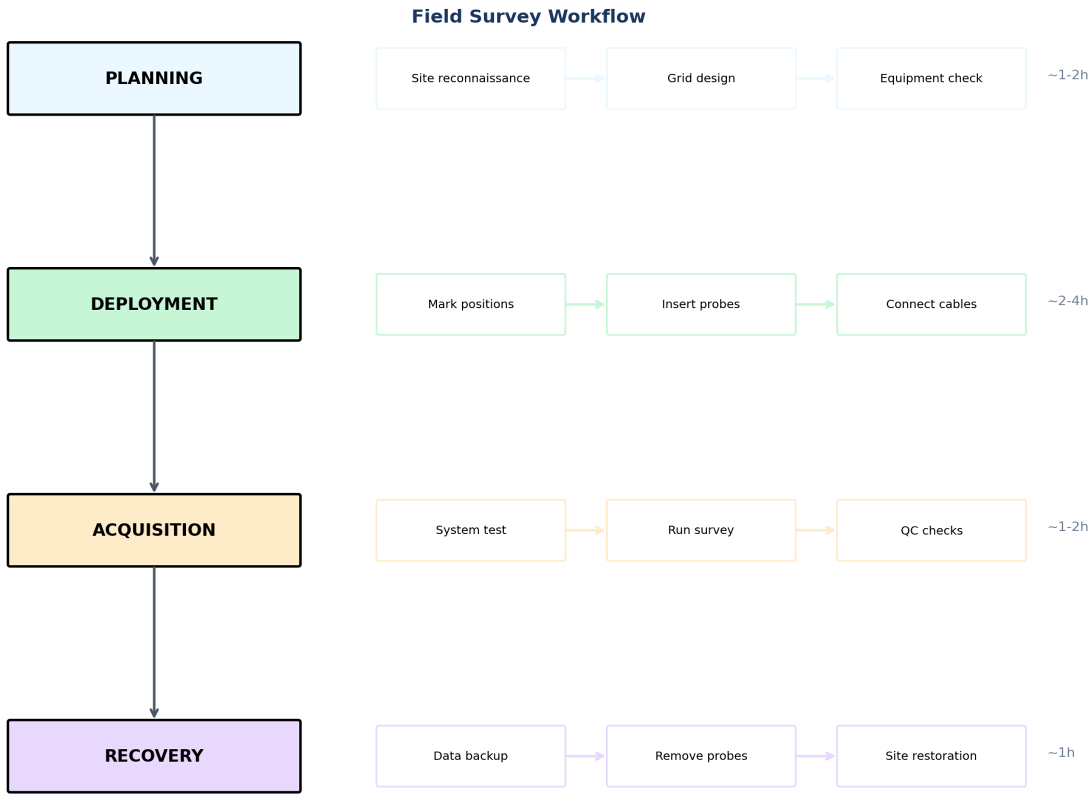


Figure 6. Complete field survey workflow showing four phases: Planning (site reconnaissance, grid design, equipment check), Deployment (marking, insertion, cabling), Acquisition (system test, survey execution, QC checks), and Recovery (backup, extraction, restoration).

Workflow Steps

1. **Install All Probes:** Deploy complete array, mark with numbered flags, record GPS coordinates and insertion depths.
2. **Background Scan:** Perform short MIT and ERT scan outside suspected zone to establish baseline/control measurements.
3. **MIT Sweep:** Complete full TX-RX matrix at all frequencies before moving probes.
4. **ERT Patterns:** Execute all injection patterns with multiple baselines for redundancy.
5. **Quality Control:** Repeat 5-10% of TX-RX pairs, verify reciprocity (A-B approximately equals B-A), document any anomalies.
6. **Extract and Move:** Carefully extract probes, shift to next section with one-column overlap for data continuity.

10.9 Quality Checks

Real-time quality assessment during data acquisition prevents costly re-surveys. Monitor the following indicators throughout the measurement process:

Good Data Indicators

- Consistent reciprocity: TX(A)-RX(B) matches TX(B)-RX(A) within 5%

• Smooth spatial variations without abrupt discontinuities
• Expected depth sensitivity decay with increasing offset
• Stable baseline measurements throughout survey

Problematic Data Indicators

- Poor reciprocity (>10% difference) - check coupling, recalibrate
- Noisy/spiky readings - check connections, improve shielding
- No depth sensitivity - verify spacing, adjust frequency
- Inconsistent repeats - check timebase synchronization, connector integrity

10.10 Deployment Scenarios

Different site conditions require adapted deployment strategies. The following scenarios illustrate common configurations optimized for specific survey objectives.

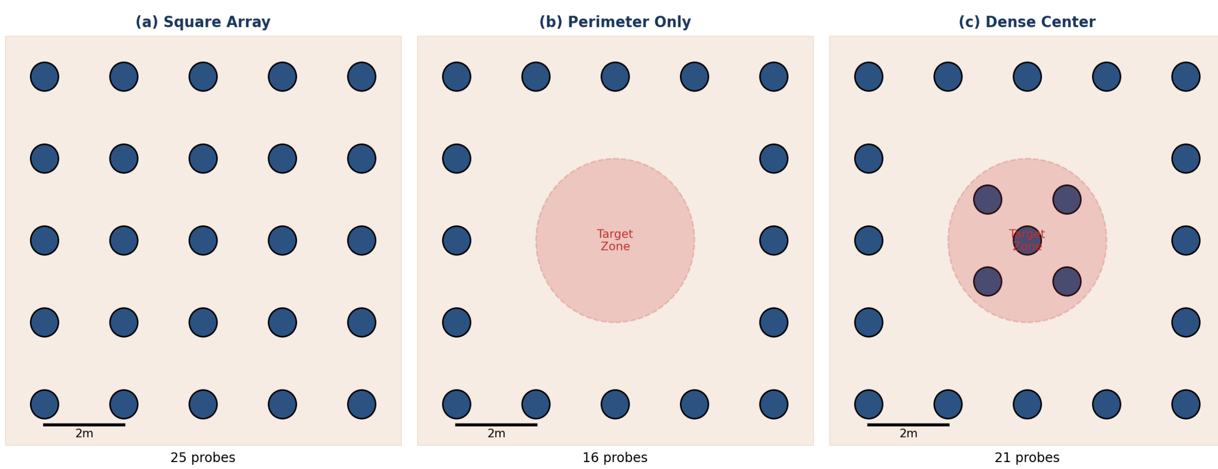


Figure 7. Deployment scenario configurations. (a) Square Array: uniform coverage for general surveys (25 probes). (b) Perimeter Only: ring deployment around known target zone for minimal disturbance (16 probes). (c) Dense Center: enhanced resolution over target with perimeter context (21 probes).

Minimal-Intrusion Variants

Rim-Only Deployment

• Place ring of probes around suspected feature edge
• Add select probes angled inward for cross-coverage
• Reduces ground disturbance in sensitive archaeological contexts
• Provides adequate coverage with proper geometric factor correction

Shallow Mode

• Insert probes to 1 m or less
• Use wider spacing (2-3 m) to compensate
• Rely on lower frequencies (2-5 kHz) for deeper field penetration

• Suitable for extremely sensitive sites or regulatory constraints

10.11 Time Estimates

Activity	Duration	Team Size	Notes
Setup (probe insertion)	30-60 min	2-3	Varies with soil
MIT sweep (all frequencies)	30-45 min	1	Automated
ERT patterns	15-30 min	1	Multiple configurations
QC checks	10-15 min	1	Repeat measurements
Extraction	15-30 min	2-3	Care required
Total per section	**2-3 hours**	2-3	10x10 m, 20 probes

Table 6. Time estimates for standard 10x10 m section survey

10.12 Shutdown and Data Backup

Safe Shutdown Procedure

1. **Complete final measurement:** Take final data set and verify data is saved.
2. **Power down:** Stop measurement software, power off base hub, disconnect cables from probes.
3. **Extract probes:** Pull gently with straight vertical motion, do not twist excessively, note any stuck probes.
4. **Site restoration:** Fill probe holes as required by permit, remove all markers and equipment, photograph final site condition.

Probe Extraction Tips

Stuck Probe Recovery

- Work probe back and forth gently with slow oscillation
- Add water around probe shaft to lubricate soil interface
- Use extraction handle tool if available
- Do not use excessive force - risk of probe damage
- For collapsed holes, allow water to soften soil before retry

Data Backup Procedure

1. **Download data:** Connect tablet/laptop to base hub, download all raw data files, verify file sizes are non-zero.
2. **Backup to multiple locations:** Copy to laptop hard drive, copy to USB drive, upload to cloud storage if connectivity available.
3. **Data organization:** Use consistent naming (SITE_DATE_SCAN#.dat), create folder per site/day, include field notes file.
4. **Verify backups:** Open files in viewer software, check data completeness, note any missing or corrupted files immediately.

10.13 Safety Reminders

Field Safety Checklist

- Always inform someone of your field location and expected return time
- Stay hydrated and take regular breaks, especially in hot conditions
- Be aware of wildlife, terrain hazards, and site-specific dangers
- Follow all site-specific safety rules and permit requirements
- Keep first aid kit accessible and know location of nearest medical facility
- For UXO sites: EOD clearance required, soft insertion tools only, 100 m exclusion zone

10.14 Equipment Maintenance and Storage

Post-Survey Cleaning

- **Rods:** Wipe down with damp cloth to remove soil and clay. Do not use solvents.
- **Threads:** Clean M12 threads with a soft brush (toothbrush). Grit in threads causes seizing.
- **Connectors:** Inspect for dirt. Use compressed air or contact cleaner if needed.
- **Cables:** Wipe clean while coiling. Check for nicks in insulation.

Storage

- **Batteries:** Store LiFePO4 batteries at 50-60% charge if unused for >1 month.
- **O-Rings:** Lightly grease O-rings with silicone grease to prevent drying.
- **Coiling:** Use 'over-under' coiling method to prevent cable twisting.
- **Environment:** Store in dry, cool location to prevent mold or thermal cycling damage.

For quick reference procedures, see Section 15: Quick Reference Card. For troubleshooting guidance, see Section 13: Troubleshooting. For calibration procedures, see Section 9: Calibration.

Section 11: Data Recording

Data Formats, File Organization, and Logging Procedures

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

11.1 Overview

This section specifies the data formats and organization for HIRT field measurements. Consistent data recording ensures reliable post-processing and long-term data management. The HIRT system generates two primary data types: Magnetic Induction Tomography (MIT)measurements and Electrical Resistivity Tomography (ERT) measurements, each requiring specific record formats to capture all relevant parameters.

All data files use CSV (Comma-Separated Values) format for maximum compatibility with analysis software. Field logs supplement electronic records with contextual information that may affect data interpretation. The combination of structured electronic records and detailed field notes enables comprehensive quality assessment during post-processing.

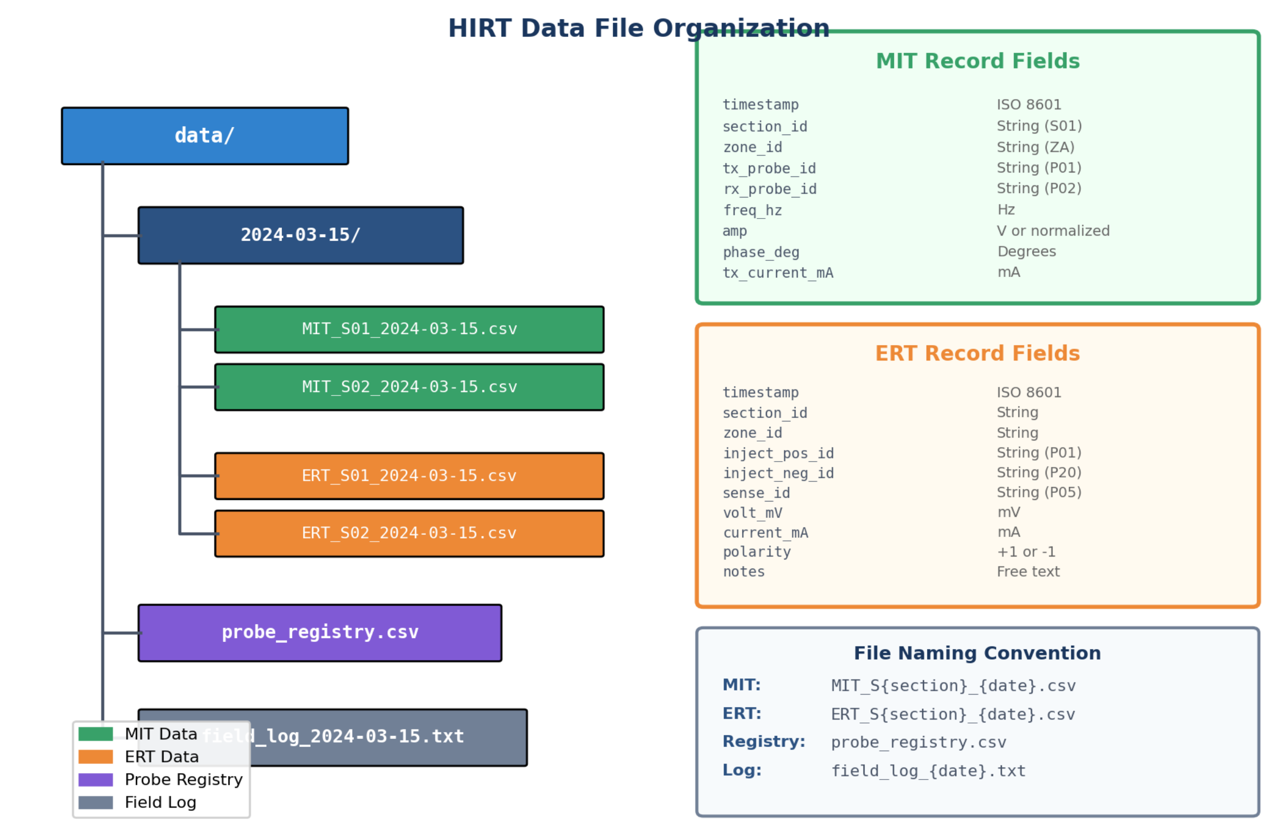


Figure 1. HIRT data file organization showing directory structure, file naming conventions, and record field definitions for MIT and ERT data types. Each survey date creates a separate subdirectory containing section-specific measurement files.

11.2 MIT Record Format

Each MIT measurement records the electromagnetic coupling between a transmitter-receiver probe pair. The record captures both the measurement geometry (which probes, which zone) and the signal parameters (amplitude, phase, frequency) needed for tomographic reconstruction.

Field	Description	Units/Format
timestamp	Measurement time	ISO 8601 or Unix
section_id	Survey section identifier	String (e.g., "S01")
zone_id	Zone Hub identifier	String (e.g., "ZA")
tx_probe_id	Transmitting probe ID	String (e.g., "P01")
rx_probe_id	Receiving probe ID	String (e.g., "P02")
freq_hz	Measurement frequency	Hz
amp	Signal amplitude	V or normalized
phase_deg	Phase angle	Degrees
tx_current_mA	TX coil current	mA

Table 1. MIT record format fields

11.3 ERT Record Format

ERT measurements record the voltage response to injected current, capturing the four-electrode geometry (two injection electrodes, one sense electrode) and the resulting potential. Polarity reversal measurements are recorded separately to enable electrode polarization correction during processing.

Field	Description	Units/Format
timestamp	Measurement time	ISO 8601
section_id	Survey section identifier	String
zone_id	Zone Hub identifier	String
inject_pos_id	Positive current probe ID	String
inject_neg_id	Negative current probe ID	String
sense_id	Voltage sensing probe ID	String
volt_mV	Measured voltage	mV
current_mA	Injected current	mA
polarity	Current direction	+1 or -1
notes	Additional notes	Free text

Table 2. ERT record format fields

Example ERT Record

```
timestamp,section_id,inject_pos_probe_id,inject_neg_probe_id,sense_probe_id,volt_mV,current_mA,
polarity,notes
2024-03-15T10:45:12Z,S01,P01,P20,P05,12.5,1.2,+1,
2024-03-15T10:45:13Z,S01,P01,P20,P06,8.3,1.2,+1,
2024-03-15T10:45:14Z,S01,P01,P20,P05,-12.4,1.2,-1,reversed polarity
```

11.4 Probe Registry

Each probe in the HIRT system has a registry entry documenting its physical characteristics and calibration status. The probe registry is a shared file that applies across all surveys and enables consistent data interpretation even when probes are swapped between deployments.

Field	Description	Units/Format
probe_id	Unique probe identifier	String
coil_L_mH	TX coil inductance	mH
coil_Q	Coil Q factor	Dimensionless
rx_gain_dB	RX amplifier gain	dB
ring_depths_m	ERT ring depths	m (comma-separated)
firmware_rev	Firmware version	String
calibration_date	Last calibration date	YYYY-MM-DD
notes	Additional notes	Free text

Table 3. Probe registry fields

Example Probe Registry

```
probe_id,coil_L_mH,coil_Q,rx_gain_dB,ring_depths_m,firmware_rev,calibration_date,notes
P01,1.2,25,40,0.5,1.5,v1.2,2024-03-10,
P02,1.15,28,40,0.5,1.5,v1.2,2024-03-10,
P03,1.18,26,40,0.5,1.5,v1.2,2024-03-10,
```

11.5 Recording Workflow

The HIRT data recording workflow follows a systematic process from site preparation through data backup. Each measurement loop captures MIT and ERT data for all probe pairs in a section before moving to the next section. Quality checks at multiple stages ensure data integrity before final storage.

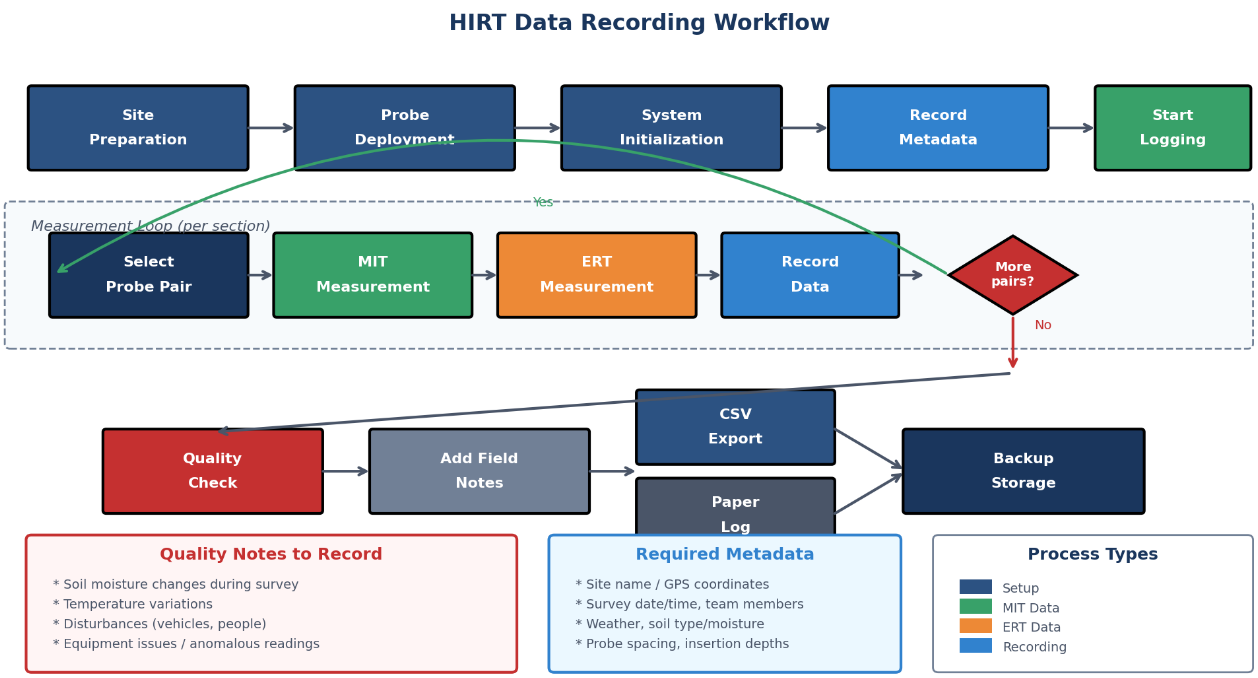


Figure 2. Data recording workflow from field setup through storage. The measurement loop iterates through all probe pairs within each section, recording both MIT and ERT data before advancing. Quality checks and field notes are captured before final backup to multiple storage locations.

11.6 Data Storage

File Organization

- **One CSV file per section** for MIT data
- **One CSV file per section** for ERT data
- **One registry file** for all probes (shared across surveys)
- **Paper log** for conditions and notes (backup)

Naming Convention

- MIT: `MIT_S{section_id}_{date}.csv`
- ERT: `ERT_S{section_id}_{date}.csv`
- Registry: `probe_registry.csv`
- Field Log: `field_log_{date}.txt`

11.7 Metadata Requirements

Site Information

- Site name and GPS coordinates
- Survey date and time (start/end)
- Team members present
- Weather conditions (temperature, precipitation, wind)
- Soil type and estimated moisture content
- Site access notes and restrictions

Measurement Parameters

- Frequency list for MIT measurements
- Current levels for ERT measurements
- Probe spacing configuration
- Insertion depths achieved
- Grid coordinates and orientation

11.8 Data Quality Notes

Field conditions that may affect data quality should be recorded in the paper log or the notes field of individual records. These annotations are critical for proper interpretation during post-processing and help identify measurements that may require special handling or exclusion from analysis.

Record in Paper Log or Notes Field

- Soil moisture changes during survey
- Temperature variations (especially for long surveys)
- External disturbances (vehicles, people, machinery)
- Equipment issues or malfunctions
- Anomalous readings with contextual explanation
- Probe insertion difficulties or obstructions

11.9 Best Practices

1. **Verify file integrity** after each section by checking record counts match expected probe pair combinations.
2. **Backup data** to at least two locations before leaving the field site.
3. **Timestamp all entries** using ISO 8601 format for unambiguous date/time parsing.
4. **Document probe positions** with photographs showing grid layout and reference markers.
5. **Record baseline readings** before and after each survey session to detect drift.
6. **Note environmental changes** including passing weather fronts, irrigation events, or traffic patterns.

Data Integrity Warning

- Never modify raw data files after collection
- Create processed copies for any transformations
- Maintain chain of custody documentation for forensic applications
- Store original files in read-only archive locations

11.10 Software Compatibility Roadmap

The CSV data formats described above are designed as raw intermediate storage. Future software tools will provide import scripts to convert these raw logs into standard formats for open-source inversion frameworks:

- **EIDORS (Matlab/Octave):** Import script will generate .mat structures for MIT-3D finite element reconstruction.
- **pyGIMLi (Python):** Converters will map ERT data to the Unified Data Format for coupled inversion.
- **ResIPy:** Direct import support for ERT .csv files is planned.

Section 12: Data Interpretation

HIRT Field Data Analysis, Tomographic Inversion, and Anomaly Interpretation

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

12.1 Overview

This section provides comprehensive guidance on interpreting HIRT field data, including depth of investigation, lateral resolution, and what each measurement method detects. Effective interpretation requires understanding both the physics of the measurements and the geological/archaeological context of the survey site.

12.2 Data Processing Pipeline

HIRT data processing follows a systematic pipeline from raw field acquisition through final interpretation. Each stage validates and refines the data to produce reliable subsurface images.

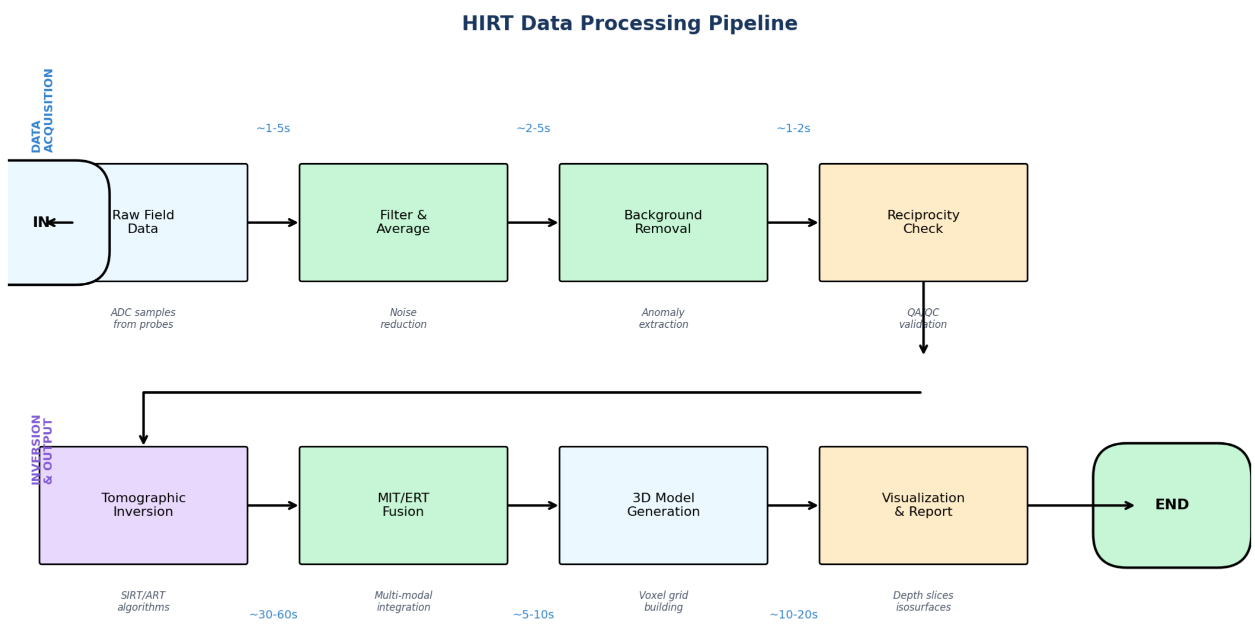


Figure 1. HIRT data processing pipeline from raw field measurements through tomographic inversion to final 3D visualization. Processing times shown are typical for a 4x4 probe grid survey.

Processing Stages

1. **Data Acquisition:** Raw ADC samples collected from probe pairs
2. **Filter and Average:** Noise reduction through digital filtering and stacking
3. **Background Removal:** Subtract homogeneous response to isolate anomalies
4. **Reciprocity Check:** Validate A-to-B equals B-to-A for quality assurance

5. **Tomographic Inversion:** Reconstruct 3D conductivity/resistivity distribution
6. **MIT/ERT Fusion:** Combine multi-modal data for comprehensive interpretation
7. **3D Model Generation:** Build voxel grid from inverted data
8. **Visualization:** Generate depth slices, isosurfaces, and reports

12.3 Depth of Investigation

The achievable investigation depth depends on several factors including probe depth, probe spacing, soil conductivity, and measurement frequency. Understanding these relationships is essential for survey planning and result interpretation.

Factors Affecting Depth

- **Probe depth:** Deeper insertion enables deeper sensitivity
- **Probe spacing:** Wider spacing increases depth but reduces lateral resolution
- **Soil conductivity:** Lower conductivity enables deeper signal penetration
- **Frequency (MIT):** Lower frequency provides deeper sensitivity
- **Current geometry (ERT):** Longer baselines enable deeper investigation

Configuration	MIT Depth	ERT Depth	Combined	Confidence
1.5m probes, 1.5m spacing	1.5-2.5m	2-3m	2-3m	HIGH
1.5m probes, 2.0m spacing	2-3m	2-3m	2-3m	HIGH
3.0m probes, 2.0m spacing	3-4m	3-5m	3-5m	MEDIUM
3.0m probes, 2.5m spacing	3-4m	4-6m	4-6m	LOW

Table 1. Depth of investigation by configuration

The commonly cited '3-6m' depth range represents favorable conditions only. For most field conditions, expect 2-4m typical depth, with up to 5-6m achievable in optimal soil conditions with longer probes and wider spacing.

12.4 Lateral Resolution

Lateral resolution approximately equals 0.5 to 1.5 times the probe spacing. Tighter spacing provides finer resolution but requires more survey time, while wider spacing offers faster coverage with coarser resolution.

Spacing	Lateral Resolution	Best Application
1.0 m	0.5-1.5 m	High-resolution burial/artifact search
1.5 m	0.75-2.25 m	Standard WWII crash investigation
2.0 m	1.0-3.0 m	Large feature reconnaissance

Table 2. Resolution by probe spacing

12.5 HIRT vs Surface Methods

HIRT's crosshole geometry provides 2-5 times better resolution than surface methods at depths greater than 2m. This advantage increases with depth due to direct ray paths and elimination of surface clutter.

Method	Lateral Res.	Depth Res.	At 3m Depth
Surface Magnetometry	1-2m	Poor	~2m lateral
GPR (in sand)	0.3-0.5m	0.05-0.1m	Degrades to 1m+
GPR (in clay)	Limited	Limited	Often fails
Surface ERT (Wenner)	~1x spacing	~0.5x spacing	~2-3m
HIRT (1.5m spacing)	0.75-1.5m	0.5-0.75m	~1m lateral
HIRT (2m spacing)	1-2m	0.5-1m	~1.5m lateral

Table 3. Resolution comparison: HIRT vs surface methods

Why HIRT Achieves Better Resolution

- Direct ray paths through target volume (not down-and-back)
- No surface clutter from topography and cultural noise
- True 3D sampling enables genuine tomographic reconstruction
- Better depth discrimination between targets at different depths

12.6 Anomaly Classification

MIT and ERT respond differently to various subsurface features. Understanding these response characteristics enables accurate classification of detected anomalies.

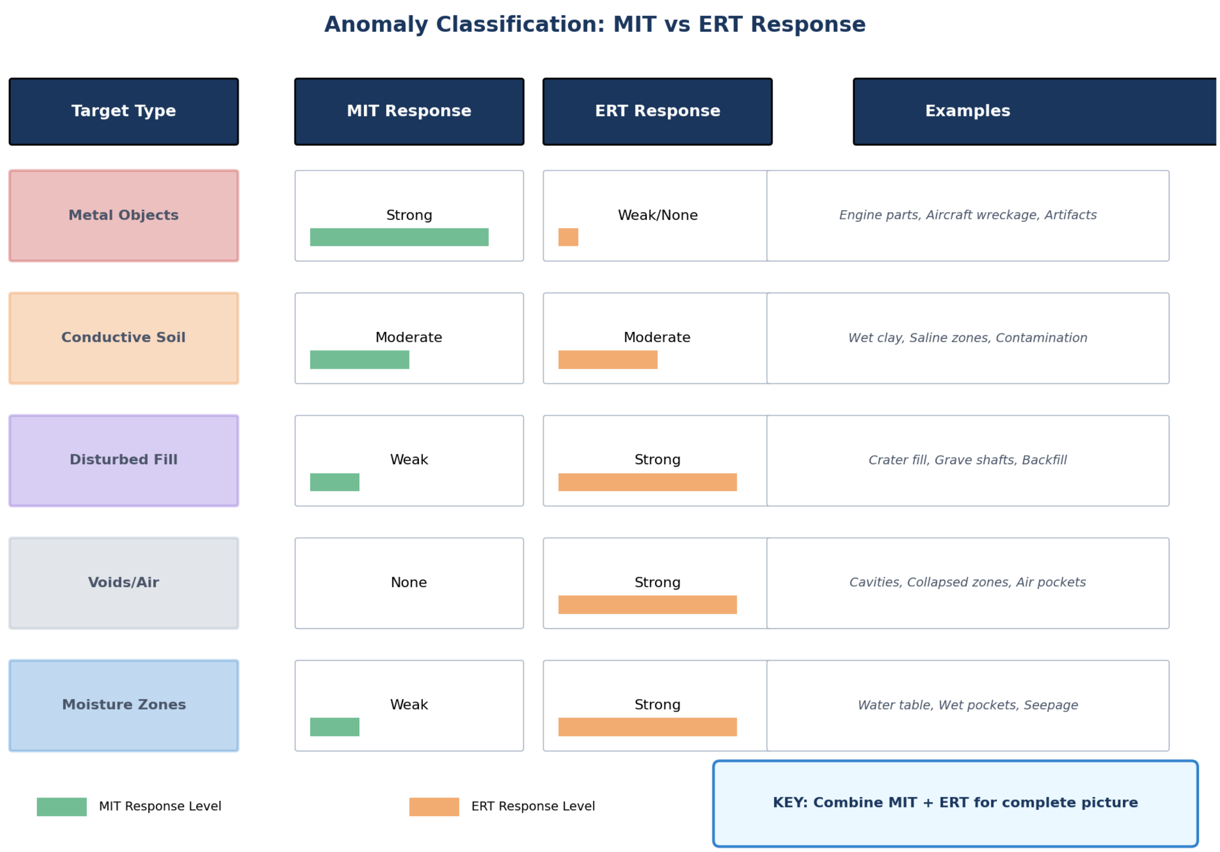


Figure 2. Anomaly classification chart showing expected MIT and ERT response levels for common target types encountered in archaeological and forensic investigations.

MIT (Magneto-Inductive Tomography) Detection

- **Metal objects:** Strong response to aluminum, steel, and iron
- **Conductive regions:** Moderate response to saline water, clay layers
- **Eddy current anomalies:** Metallic wreckage produces characteristic signatures
- Phase lag indicates conductivity; amplitude indicates size/distance
- Higher frequencies provide better near-surface sensitivity

ERT (Electrical Resistivity) Detection

- **Disturbed fill:** Different compaction and moisture than native soil
- **Moisture variations:** Wet zones appear as low resistivity
- **Crater walls:** Clear boundaries between fill and native soil
- **Voids:** Air-filled spaces show very high resistivity
- Depth slices reveal layering and lateral extent of features

12.7 Example Tomogram Interpretation

The following example demonstrates combined MIT and ERT interpretation for a simulated WWII crash site investigation. Note how the complementary data streams provide more complete subsurface characterization than either method alone.

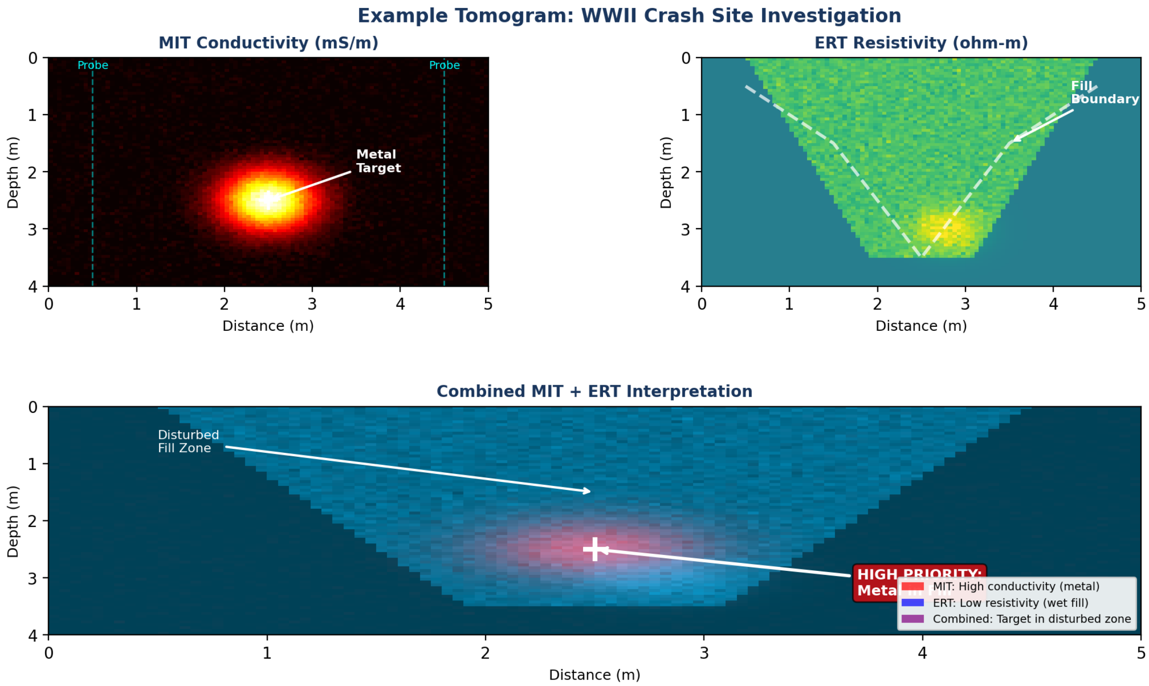


Figure 3. Example tomogram showing MIT conductivity (top left), ERT resistivity (top right), and combined interpretation (bottom). The metal target within the disturbed fill zone is identified as a high-priority excavation target.

Interpretation Notes

- MIT clearly identifies the metal concentration at 2.5m depth
- ERT reveals the crater fill geometry and moisture distribution
- Combined view shows the target context within disturbed ground
- High-priority designation indicates both metal and disturbed fill present

12.8 Combined Interpretation Strategy

Effective HIRT interpretation combines MIT and ERT results with site context and historical information. The following decision tree provides systematic guidance for prioritizing investigation targets.

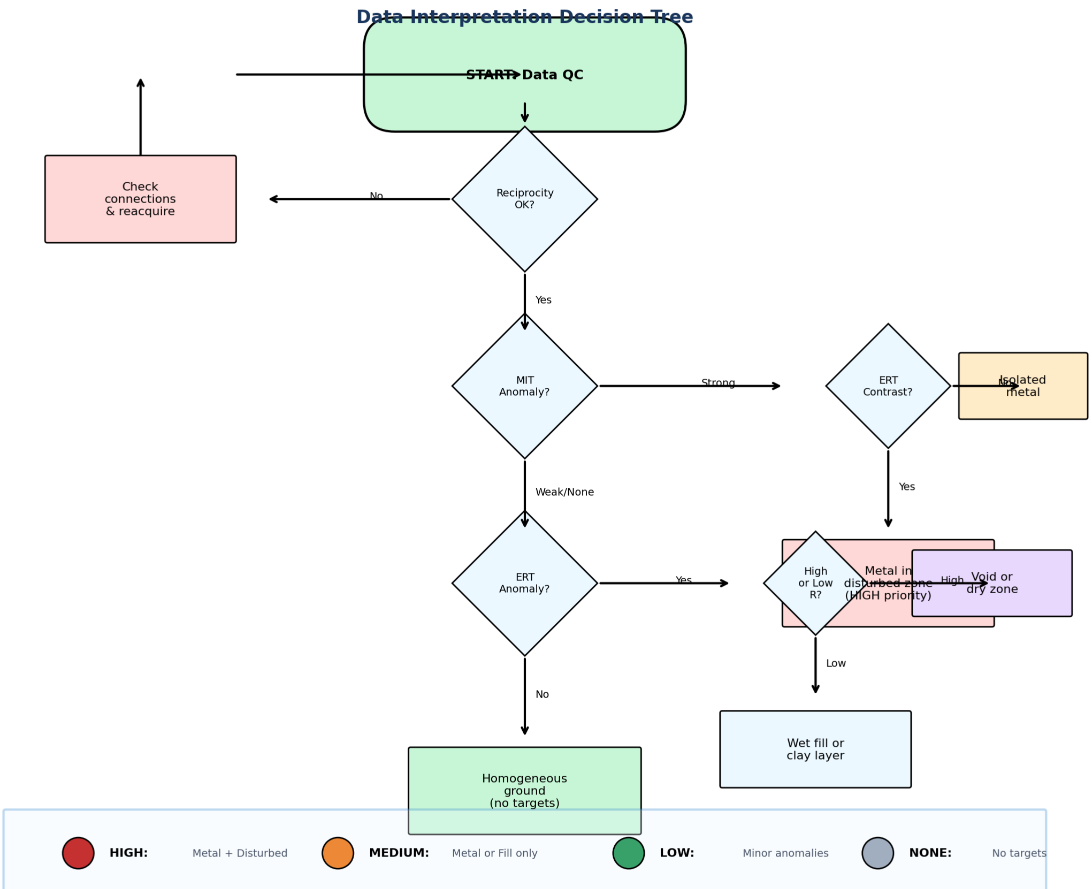


Figure 4. Data interpretation decision tree for prioritizing HIRT survey results. Begin with data quality verification, then evaluate MIT and ERT anomalies to assign investigation priority levels.

Example Interpretation Scenarios

Scenario 1: Bomb Crater Investigation

- **MIT:** Metal parts detected near crater base (aluminum/steel fragments)
- **ERT:** Fill bowl geometry visible, wet pockets at base, clear crater walls
- **Interpretation:** Classic impact crater with retained metallic debris

Scenario 2: Woods Burial Search

- **MIT:** Small metallic clusters (buckles, dog tags, buttons)
- **ERT:** Rectangular disturbed zone with different moisture profile
- **Interpretation:** Possible grave shaft requiring careful investigation

Scenario 3: Aircraft Wreckage

- **MIT:** Large conductive masses (engine block, landing gear)
- **ERT:** Disturbed ground pattern, possible fuel contamination zones
- **Interpretation:** Significant wreckage concentration warranting excavation

12.9 Data Quality Indicators

Good Data Characteristics

- Consistent reciprocity (A-to-B approximately equals B-to-A)
- Smooth spatial variations without erratic jumps
- Expected depth sensitivity matching configuration
- Stable baseline measurements over survey duration

Problematic Data Warning Signs

- Poor reciprocity indicates coupling problems or calibration drift
- Noisy/spiky readings suggest connection issues or EMI
- No depth sensitivity may indicate inadequate spacing or frequency
- Inconsistent repeats require checking timebase and connectors

12.10 Field Expectations and Detection Limits

Typical Anomaly Sizes

Target Type	Typical Size	Expected Response
Large metal (engine)	1-3 m	Strong MIT response
Small metal (artifacts)	0.1-0.5 m	Weaker MIT, requires tight spacing
Grave shaft	0.5-1.5 m wide	Clear ERT contrast
Crater fill	10-15 m diameter	ERT shows boundaries clearly

Table 4. Typical anomaly sizes and expected responses

Detection Limits

- **MIT:** Can detect ~0.1m metal at 1-2m depth (size dependent)
- **ERT:** Can resolve ~0.5m features at 1-2m depth
- **Depth:** Practical limit 2-4m typical with 3m probes (5-6m in optimal conditions)

12.11 Post-Survey Workflow

1. **QA/QC:** Verify data quality and reciprocity
2. **Inversion:** Reconstruct 3D models using appropriate algorithms
3. **Fusion:** Combine MIT and ERT results for complete picture
4. **Visualization:** Generate depth slices and 3D isosurfaces
5. **Interpretation:** Correlate anomalies with site context
6. **Reporting:** Document findings with confidence assessments
7. **Planning:** Recommend excavation priorities and methods

Key Interpretation Principles

- Always combine MIT and ERT for complete subsurface picture
- Consider site history and expected target characteristics
- Use confidence levels to guide excavation prioritization
- Document interpretation rationale for future reference

12.12 Mathematical Basis of Reconstruction

For scientific rigor, it is important to define the physical models governing the reconstruction algorithms. The inversion process solves the 'inverse problem': finding the subsurface property distribution that best explains the measured data.

Forward Models

MIT (Quasi-Static Maxwell's Equations): The secondary magnetic field B_s generated by eddy currents in a conductive medium is governed by:

$$\mathrm{curl}\, E = -i \cdot \omega \cdot B$$

$$\mathrm{curl}\, H = \sigma \cdot E + J_s$$

Where sigma is conductivity, omega is angular frequency, and J_s is the source current.

ERT (Poisson's Equation): The electric potential phi distribution due to a current source I in a medium of conductivity sigma is governed by:

$$\mathrm{div}\, (\sigma \cdot \mathrm{grad}\, \phi) = -I \cdot \delta(r - r_s)$$

Inverse Problem Formulation

The reconstruction minimizes an objective function Phi comprising data mismatch and model roughness (regularization):

$$\Phi(m) = \| d_{obs} - F(m) \|^2 + \lambda \cdot \| R \cdot m \|^2$$

Where d_{obs} is observed data, F(m) is the forward model output for model m, R is the roughness matrix, and lambda is the regularization parameter. This is typically solved using a Gauss-Newton iterative update:

$$m_{k+1} = m_k - (J^T J + \lambda R^T R)^{-1} J^T (d_{obs} - F(m_k))$$

Where J is the Sensitivity Matrix (Jacobian) describing how data changes with model parameters.

Section 13: Troubleshooting

Diagnostic Approaches and Solutions for HIRT Field Operations

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

Overview

This section provides diagnostic approaches and solutions for common issues encountered during HIRT field operations. Systematic troubleshooting ensures minimal downtime and maximum data quality during surveys.

13.1 Diagnostic Approach

System Check Procedure

When issues arise, follow this systematic check procedure:

1. **Hub Power:** Verify the Central Hub power LED is green.
2. **Zone Continuity:** Check continuity between Hub Trunk port and Probe tip (using DMM).
3. **Trunk Seating:** Ensure all DB25/Trunk connectors are fully seated and screwed in.
4. **MIT Baseline:** Verify TX to RX coupling on two probes in air before insertion.

Quick Reference Table

Symptom	Likely Cause	Fix
RX saturation on nearby probes	TX too strong	Lower TX level; rotate coils to orthogonal
Noisy MIT data	Trunk shielding issue	Check trunk cable ground; verify star ground
Unstable ERT voltages	Poor soil contact	Pre-moisten hole; apply saline gel
Zone Hub not detected	Trunk disconnected	Inspect DB25 pins; reseat Trunk Cable
Inconsistent repeats	Thermal drift	Allow 15 min warmup; check Hub fans

Table 1. Common symptoms, causes, and solutions

Diagnostic Decision Tree

The following decision tree provides a systematic approach to diagnosing HIRT system issues, from initial symptom identification through resolution.

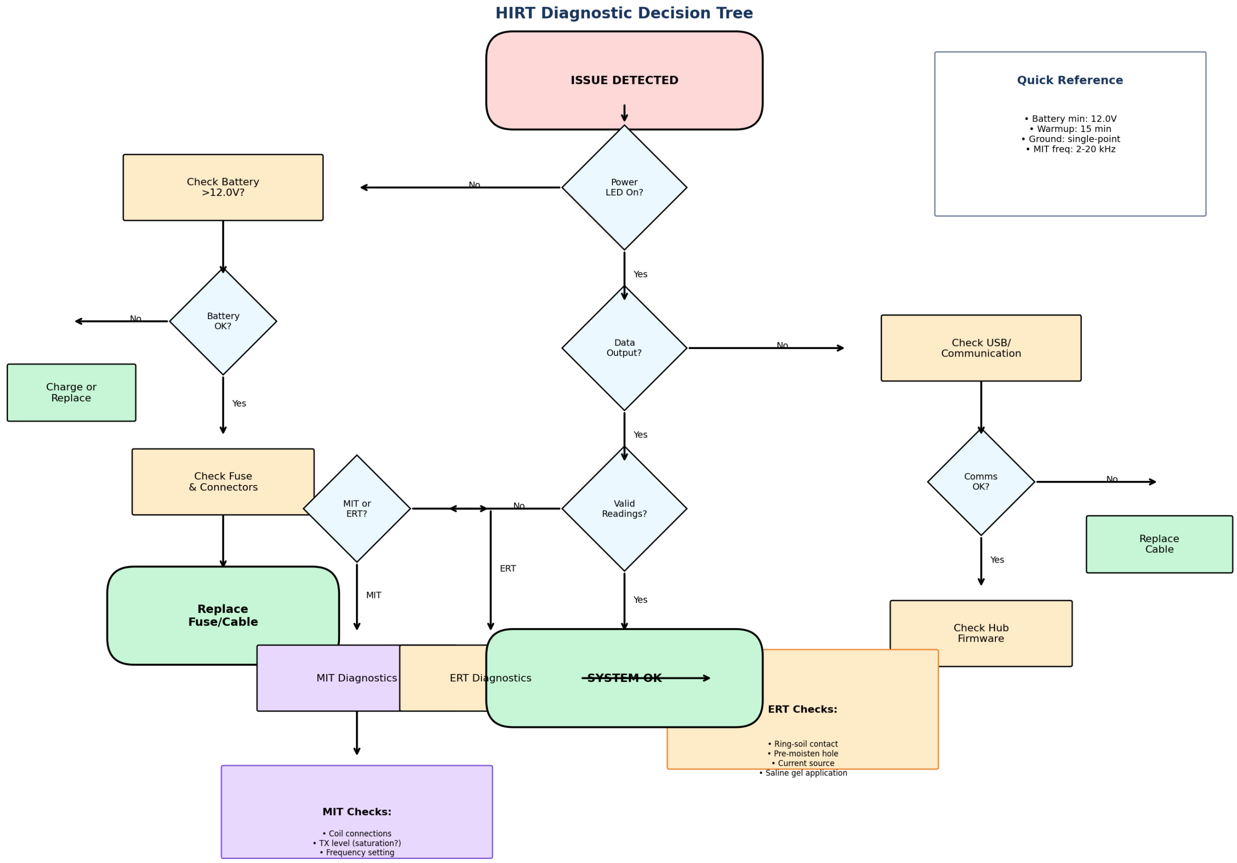


Figure 1. Comprehensive diagnostic decision tree for HIRT troubleshooting. Follow the flowchart from the top to systematically identify and resolve issues.

13.2 MIT Troubleshooting

RX Saturation on Nearby Probes

Symptoms: Amplitude readings maxed out on nearby probes, phase readings erratic or stuck, effects only visible on probes close to TX.

Causes: TX output too high for close-range measurements, direct magnetic coupling between TX and RX coils, insufficient separation or poor coil orientation.

Solutions:

1. **Reduce TX level:** Lower DDS output or TX driver gain
2. **Increase separation:** Use wider probe spacing for close pairs
3. **Rotate coils:** Ensure TX and RX coils are orthogonal
4. **Add attenuation:** Use lower gain on RX for nearby probes
5. **Skip close pairs:** Do not measure TX to RX pairs less than 0.5 m apart

Noisy MIT Data

Symptoms: High noise floor, erratic amplitude/phase readings, inconsistent measurements between sweeps.

Causes: Poor cable shielding, ground loops (multiple ground paths), EMI from nearby sources, insufficient integration time.

Solutions:

1. **Check shielding:** Verify all cables are properly shielded
2. **Single-point ground:** Ensure only one ground connection at Hub
3. **Twist pairs:** Use twisted-pair cables for signal lines
4. **Increase integration:** Longer measurement time reduces noise
5. **Check EMI sources:** Move away from power lines, vehicles, radios
6. **Verify connections:** Check all connectors are tight and clean

No Depth Sensitivity (MIT)

Symptoms: Measurements do not change with depth, all readings similar regardless of target depth, no response to known deep targets.

Solutions:

1. **Lower frequencies:** Use 2-5 kHz for MIT (deeper penetration)
2. **Add longer offsets:** Include TX to RX pairs with >3 m spacing
3. **Deeper probes:** Insert probes deeper if possible
4. **Check targets:** Verify expected target depths are realistic for configuration

13.3 ERT Troubleshooting

Unstable ERT Voltages

Symptoms: Voltage readings drift or jump, inconsistent measurements, poor contact indicated in diagnostic output.

Causes: Dry soil preventing good electrical contact, poor ring-to-soil contact, loose connections, polarization effects at electrodes.

Solutions:

1. **Pre-moisten hole:** Add water to improve contact
2. **Use saline gel:** Apply conductive gel around rings
3. **Check ring contact:** Ensure rings are flush with soil
4. **Reverse polarity:** Use AC or periodic polarity reversal to reduce polarization
5. **Check connections:** Verify all wiring is secure
6. **Increase current:** Slightly higher current may improve SNR

ERT Contact Problems

Symptoms: High contact resistance, erratic voltage readings, some electrodes not responding.

Solutions:

1. Verify ring contact with soil
2. Add water around probe (improve contact)
3. Check ring-to-cable connection
4. Clean rings if accessible

5. Consider relocating probe if contact remains poor

No Depth Sensitivity (ERT)

Symptoms: All measurements show surface effects only, no response to known deep features, uniform readings across array.

Solutions:

1. **Longer ERT baselines:** Corner-to-corner, edge-to-edge injections
2. **Deeper probes:** Insert probes deeper if possible
3. **Wider spacing:** Increase array dimensions

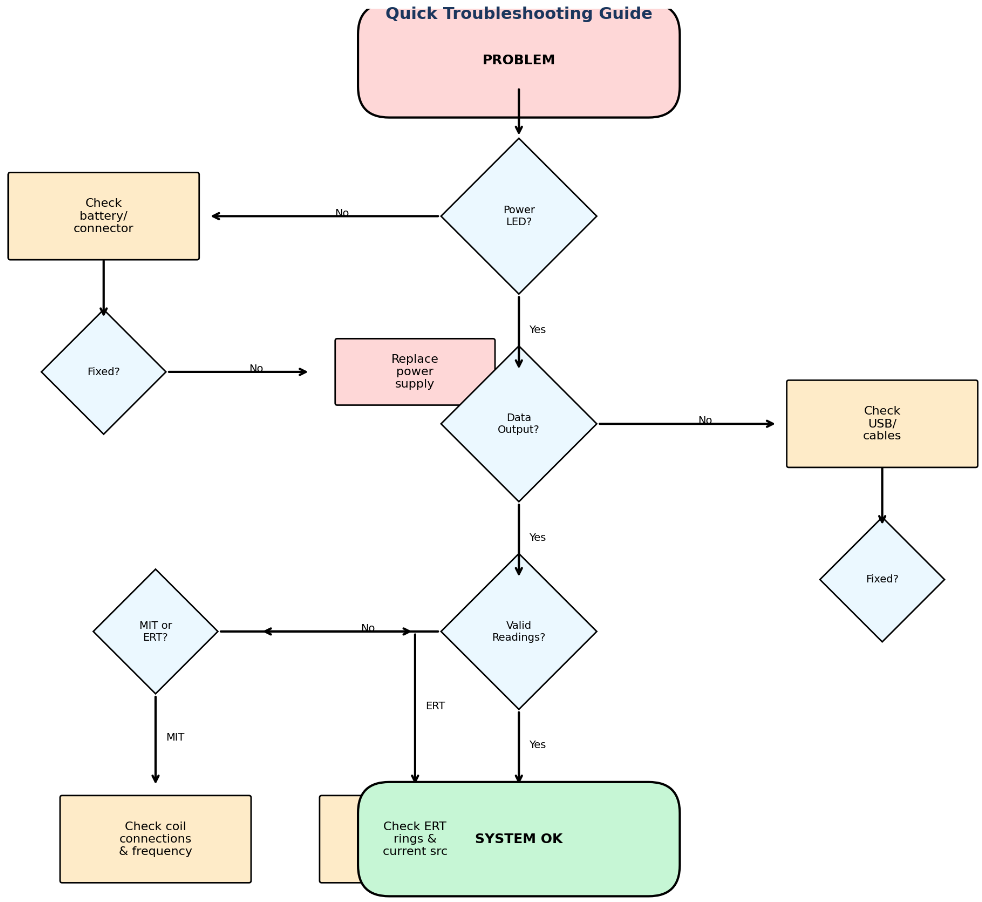


Figure 2. Quick troubleshooting flowchart for rapid issue identification. This simplified guide helps identify the most common failure modes.

13.4 Power Issues

Probe Not Responding

Symptoms: No LED indicator, no communication with base hub, probe not detected in diagnostic scan.

Solutions:

1. Check cable connections (both ends)
2. Test with multimeter (continuity)
3. Try different port on base hub
4. Swap to spare cable
5. Restart probe (disconnect/reconnect power)
6. Replace with spare probe if available

Base Hub Not Powering On

Symptoms: No power LED, no response to power switch, system completely dead.

Causes: Depleted battery, blown fuse, power switch failure.

Solutions:

1. Check battery voltage (should be >12.0 V)
2. Check fuse (replace if blown)
3. Verify power switch operation
4. Check internal connections if accessible
5. Use backup power supply if available

13.5 Communication Issues

Lost Probe Communication

Symptoms: Probe was working, now unresponsive; intermittent connection; partial data received.

Solutions:

1. Check cable connections (both ends)
2. Inspect cable for damage (kinks, cuts)
3. Clean connectors with contact cleaner
4. Swap to known-good cable
5. Check for EMI sources nearby
6. Restart probe and base hub

Sync Problems

Symptoms: Timing errors in data, inconsistent measurements between probes, data corruption.

Causes: Timebase distribution failure, clock drift, cable issues on sync line.

Solutions:

1. Verify sync signal at each probe
2. Check sync cable for damage

3. Restart measurement system
4. Re-initialize sync before continuing

13.6 Environmental Factors

Temperature Effects

Symptoms: Readings drift over time, morning vs. afternoon differences, inconsistent calibration.

Solutions:

1. Allow system to stabilize (10-15 min warmup)
2. Note temperature variations in field log
3. Apply temperature compensation if available
4. Take baseline measurements at current temperature
5. Shield equipment from direct sun if possible

Weather Impacts

Symptoms: Data quality degradation, increased noise, contact problems.

Solutions:

1. Protect connections from moisture
2. Secure cables against wind movement
3. Use weather covers for sensitive equipment
4. Postpone measurements in severe conditions

13.7 Field Repairs

Field Repair Kit

Keep these items handy for field repairs:

- Spare cables (2-3)
- Spare probes (2-4 recommended)
- Electrical tape
- Multimeter
- Small screwdriver set
- Contact cleaner spray
- Zip ties
- Heat-shrink tubing
- Solder and iron (battery powered, optional)
- Notebook and pencil (for notes)
- Calibration sheet

Emergency Cable Repair

If a cable is damaged in the field:

1. **Locate the break** (continuity test)

2. **Cut out damaged section** if possible
3. **Strip and splice** wires
4. **Insulate with tape** or heat-shrink
5. **Test before use**

Note: Field-repaired cables should be replaced at first opportunity.

Connector Cleaning

1. Apply contact cleaner to connector
2. Wipe with clean cloth
3. Allow to dry before reconnecting
4. Apply thin layer of dielectric grease (optional, for moisture protection)

13.8 When to Abort Survey

Conditions Requiring Survey Abort

• **Safety Issues:** Severe weather (lightning, high winds), site hazards discovered, equipment malfunction creating hazard

• **Data Quality:** >25% probes non-functional, persistent unusable noise, unable to achieve ground contact on majority of probes

• **Critical Failures:** Base hub failure, data logger failure, battery depletion with no backup

• **Practical Issues:** Time constraints preventing quality data, site access revoked

Before Aborting

1. Document all issues in field log
2. Save all data collected (even partial)
3. Note probe positions for potential return
4. Photograph site conditions
5. Extract probes safely if time permits
6. Backup data immediately

Partial Survey Options

If full abort is not necessary, consider these alternatives:

- **Reduce survey area** to functional probes
- **Simplify measurement protocol** (fewer frequencies, fewer patterns)
- **Focus on priority targets** only
- **Document limitations** for data interpretation

13.9 Prevention

Pre-Field Checks

- All connectors tight and clean
- Cables tested for continuity

- Calibration up to date
- Spare parts available
- Field diagnostic kit packed
- Batteries charged
- Weather forecast reviewed

During Survey

- Monitor data quality in real-time
- Check reciprocity periodically
- Note any anomalies immediately
- Keep spare probes ready
- Protect equipment from weather

Post-Survey

- Inspect all equipment
- Note any issues for repair
- Update calibration records
- Clean and store properly
- Recharge all batteries
- Restock field repair kit

Related Sections

- For detailed operating procedures, see **Section 10: Field Operations**
- For data format specifications, see **Section 11: Data Recording**
- For calibration procedures, see **Section 9: Calibration**

Section 14: Glossary

Technical Terms, Acronyms, and Definitions

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

This glossary provides definitions for technical terms, acronyms, and specialized vocabulary used throughout the HIRT whitepaper. Terms are organized alphabetically within functional categories to facilitate quick reference during system assembly, calibration, and field deployment.

Acronyms and Terms

A-D

ADC (Analog-to-Digital Converter)

- Converts analog voltage signals to digital values for processing

Amplitude

- Magnitude of a signal, typically measured in volts or normalized units

Baseline

- Distance/geometry between source and receiver probes
- Longer baselines provide deeper investigation depth

BOM (Bill of Materials)

- Complete list of components needed to build the system

Crosshole

- Measurement geometry where sensors are placed in separate boreholes/probes
- Provides true tomographic coverage through the volume

E-H

ERT (Electrical Resistivity Tomography)

- Method using current injection and voltage measurement to map soil resistivity
- Detects moisture, disturbance, voids, and soil variations

Eddy Currents

- Electrical currents induced in conductive materials by changing magnetic fields
- Cause attenuation and phase lag in MIT measurements

Ferrite Core

- Magnetic material used in coils to increase inductance and efficiency
- Typically rod-shaped for probe applications

Frequency

- Number of cycles per second, measured in Hz (Hertz)
- Lower frequencies penetrate deeper; higher frequencies provide better resolution

I-L

Inductance

- Property of a coil that resists changes in current
- Measured in Henries (H) or millihenries (mH)

Inversion

- Mathematical process to reconstruct 3D property distribution from measurements
- Software step (not covered in this hardware guide)

Lock-in Detection

- Technique to extract small signals at a known reference frequency with high SNR
- Can be analog (AD630) or digital (DSP-based)

M-P

MIT (Magnetic Induction Tomography)

- Low-frequency electromagnetic method using coils
- Measures amplitude and phase changes caused by conductive objects

MCU (Microcontroller Unit)

- Small computer on a chip (e.g., ESP32)
- Located exclusively in the Central Hub; manages signal generation, multiplexing, and data acquisition

Probe

- The passive sensor assembly inserted into the ground
- Contains only coils and electrodes; no active electronics are located downhole

Zone Hub

- A local, passive breakout box that aggregates 4 probes into a single high-density trunk cable

Trunk Cable

- A high-density shielded multi-core cable (e.g., DB25) that carries analog signals from a Zone Hub to the Central Hub

Q-T

Q Factor

- Quality factor of a coil, indicates efficiency
- Higher Q = lower losses, better performance

Reciprocity

- Principle that TX->RX measurement should equal RX->TX measurement
- Used for quality control

Resistivity

- Property of material to resist electrical current flow
- Measured in ohm-meters (ohm-m)
- High resistivity: dry soil, voids
- Low resistivity: wet soil, clay, metal

RX (Receive/Receiver)

- Receiving coil or probe that measures signals

Sensitivity Volume

- The 3D region that contributes most to a particular measurement
- Depends on probe spacing, frequency, and soil properties

U-Z

TX (Transmit/Transmitter)

- Transmitting coil or probe that generates signals

Tomography

- Imaging method that reconstructs 3D structure from multiple measurements
- Similar to medical CT scanning

UXO (Unexploded Ordnance)

- Live explosive devices that may be present at WWII sites
- Requires EOD clearance before deployment

Measurement Terms

Apparent Resistivity

- Calculated resistivity from voltage/current measurements
- May differ from true resistivity due to measurement geometry

Attenuation

- Reduction in signal amplitude
- Indicates presence of conductive objects or losses

Common-Mode Rejection

- Ability to reject signals common to both inputs
- Important for differential measurements

SNR (Signal-to-Noise Ratio)

- Ratio of signal strength to noise level
- Higher SNR = better data quality

Field Terms

Section

- Grid area surveyed in one deployment cycle
- Typically 10x10 m, manageable by small team

Node

- Probe insertion point in the grid
- Spacing determines resolution and depth

Pilot Rod

- Metal rod used to create hole for probe insertion
- Removed before inserting sensor rod

Rim Deployment

- Placing probes around perimeter rather than throughout area
- Reduces ground disturbance

Section 15: Quick Reference

Field Reference Guide for HIRT System Operation

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

This quick reference card provides essential information for field deployment of the HIRT system. Print this section as a laminated card for use in the field.

Power-Up Sequence

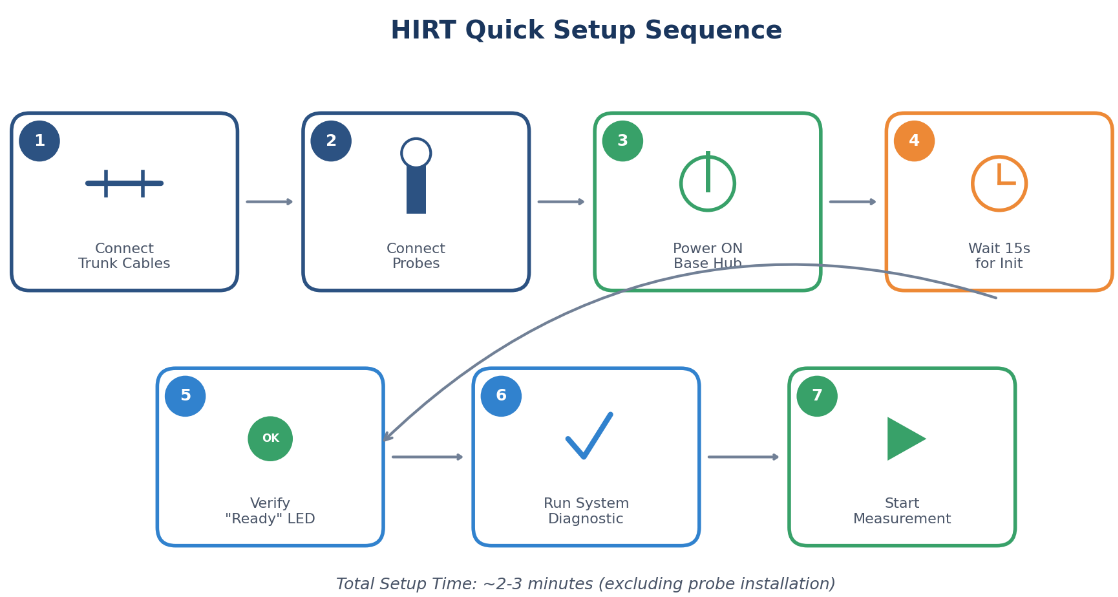


Figure 1. HIRT quick setup sequence showing the seven-step power-up procedure from cable connection to measurement initiation.

Key Parameters

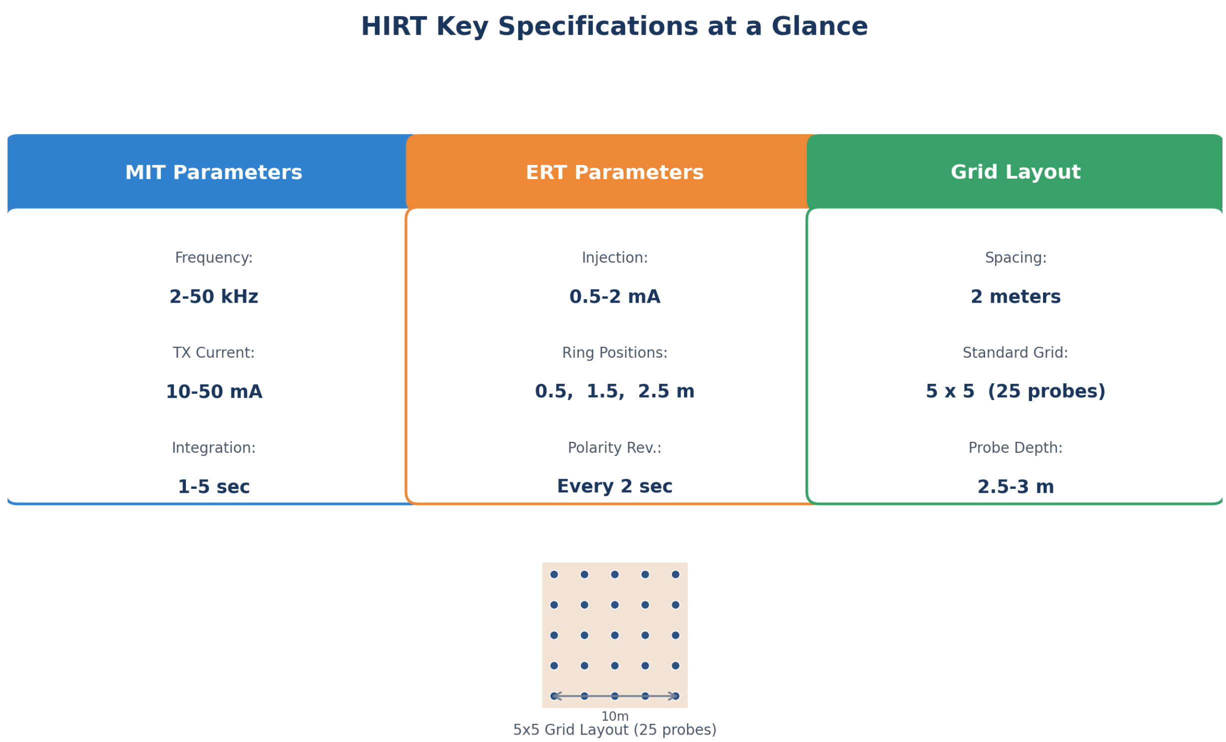


Figure 2. Key HIRT specifications for MIT (magnetic induction tomography), ERT (electrical resistivity tomography), and standard grid layout.

Standard Grid Layout (10x10 m)

```
Spacing: 2 meters Probes: 25 (5x5 grid) Depth: 2.5-3 m

0m 2m 4m 6m 8m
0m P01 P02 P03 P04 P05
2m P06 P07 P08 P09 P10
4m P11 P12 P13 P14 P15
6m P16 P17 P18 P19 P20
8m P21 P22 P23 P24 P25
```

Status LEDs (Central Hub)

LED	Solid	Blink	Off
PWR	OK	Low Battery	No Power
TX	Active	Scanning	Idle
LOG	Log Active	SD Error	No Log
ERR	System Fault	Port Warning	OK

Table 1. Central Hub LED status indicators

Cable Color Code

Wire Color	Function
Red	Power +
Black	Power GND
White	TX+
Green	TX-
Blue	RX+
Yellow	RX-
Shield	Ground

Table 2. Standard cable wire color assignments

Probe Connector Pinout

Pin	Signal	Pin	Signal
1	TX+	5	Guard
2	TX-	6	Ring A
3	RX+	7	Ring B
4	RX-	8	Ring C

Table 3. 8-pin probe connector pinout

Soil Type Guidelines

Soil Type	Insertion Method	ERT Contact
Sand	Direct push	Add water
Clay	Pre-drill	Good
Rocky	Careful auger	Variable
Wet	Easy	Excellent

Table 4. Soil-specific probe installation guidance

Pre-Deployment Safety Checklist

SAFETY CHECK (Complete Before Deployment)

- Site access authorized
- Underground utilities located and marked
- First aid kit available on site
- Weather conditions checked and acceptable
- Contact person informed of work location
- Equipment extraction plan ready

For detailed procedures and troubleshooting, see Section 10: Field Operation Manual and Section 13: Troubleshooting Guide.

Section 16: Field Checklists

Pre-Deployment, On-Site, and Post-Deployment Procedures

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

This section provides comprehensive checklists for HIRT field operations. These checklists ensure consistent, safe, and thorough survey procedures from initial planning through final data archival. Print these pages for use in the field.

16.1 Pre-Deployment Checklist

Permits and Legal

- ■ Permits/ethics & UXO clearance confirmed
- ■ Site access permissions obtained
- ■ Team members briefed on legal/ethical requirements
- ■ Emergency contacts documented

Equipment Preparation

- ■ Probe calibration sheet packed
- ■ All probes tested and functional
- ■ Batteries charged; spares packed
- ■ Base hub tested and ready
- ■ Cables tested for continuity
- ■ Spare probes available (2-4 recommended)

Tools and Supplies

- ■ Pilot rods available
- ■ Driver/extraction tools
- ■ Flags, tapes for marking
- ■ GPS/total station for coordinates
- ■ Notebooks and data loggers
- ■ Field diagnostic kit (multimeter, spare parts)

Documentation

- ■ Field log templates prepared
- ■ Probe registry updated
- ■ Site maps/plans available

■ Previous survey data (if applicable)

16.2 On-Site Checklist

Site Setup

■ Establish control area (background scan location)

■ Lay out section grid

■ Record coordinates (GPS/total station)

■ Document site conditions (soil, moisture, weather)

■ Mark probe positions with flags

Probe Deployment

■ Insert probes systematically

■ Verify depths & IDs match records

■ Connect Probes to Zone Boxes

■ Connect Zone Boxes to Central Hub via Trunk Cables

■ Verify Trunk Cable connectors are tight/screwed in

■ Run diagnostic continuity scan from Hub

Data Collection

■ Run background scan (control area)

■ Run MIT sweep (all TX; multi-freq)

  ■ Verify all frequencies measured

  ■ Check for saturation or errors

■ Run ERT patterns (2-4 baselines; flip polarity)

  ■ Verify current injection working

  ■ Check voltage readings reasonable

■ QC repeats (5-10% of pairs)

  ■ Verify reciprocity (A->B approx B->A)

  ■ Check consistency

Quality Control

■ Monitor data quality in real-time

■ Note any anomalies or issues

■ Document any disturbances

■ Verify time synchronization

■ Check for ground loops or noise

Section Completion

- ■ All measurements completed
- ■ Data backed up (if possible on-site)
- ■ Extract probes carefully
- ■ Move to next section (keep overlap if possible)
- ■ Update field log

16.3 Post-Deployment Checklist

Data Management

- ■ Back up CSVs to secure storage
- ■ Photo log of the grid (if taken)
- ■ Quick sanity plots (amp/phase vs distance)
- ■ Verify data completeness
- ■ Organize files by section/date

Equipment Care

- ■ Decontaminate/inspect probes
- ■ Note any repairs needed
- ■ Clean connectors and cables
- ■ Check for damage
- ■ Store equipment properly

Post-Survey Documentation

- ■ Complete field notes
- ■ Update probe registry with any changes
- ■ Document any issues encountered
- ■ Note lessons learned
- ■ Prepare preliminary report (if needed)

Follow-Up Actions

- ■ Review data quality
- ■ Identify any missing measurements
- ■ Plan next steps (additional sections, processing)
- ■ Schedule equipment maintenance

- Update procedures based on experience

16.4 Emergency Procedures

In the event of an emergency, use these checklists to ensure proper response and documentation. Safety is the top priority in all situations.

Safety Incidents

- Stop work immediately if unsafe conditions
- Evacuate if necessary
- Contact emergency services
- Document incident
- Report to site supervisor

Equipment Failure

- Isolate failed component
- Use spare if available
- Document failure for repair
- Continue with remaining probes if possible
- Adjust survey plan if needed

Data Loss Response

- Attempt recovery if possible
- Document what was lost
- Re-measure if critical
- Improve backup procedures
- Learn from incident

16.5 UXO Site Safety Visual

For humanitarian demining or UXO-sensitive sites, the following visual checklist provides a quick reference for critical safety requirements.

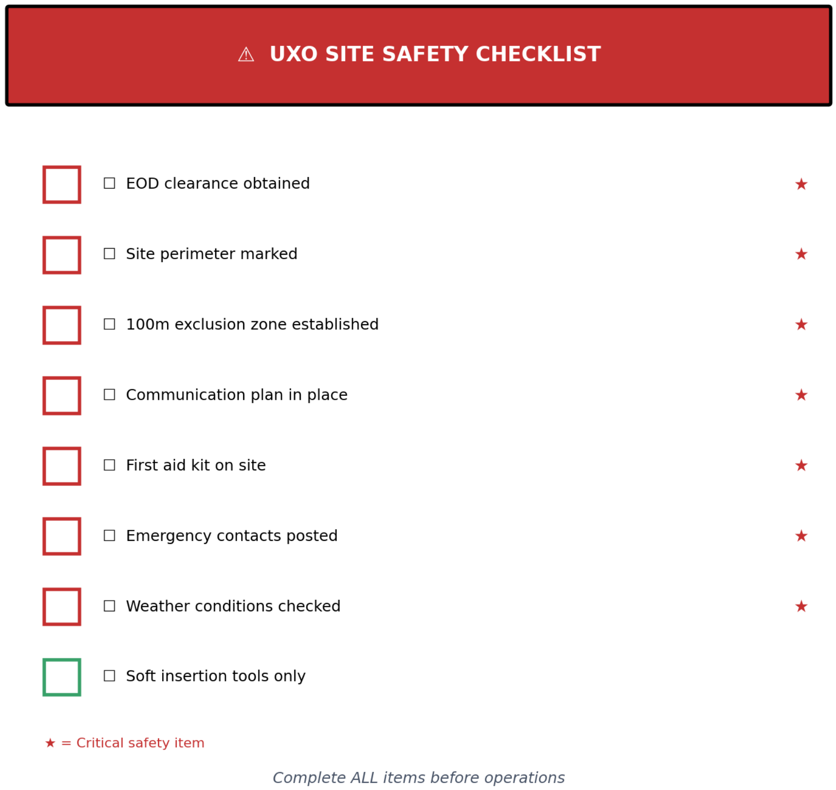


Figure 1. UXO Site Safety Checklist - Complete ALL items before operations.

16.6 Field Log Template

Use this template to record daily survey activities. Make copies as needed for each day of fieldwork. Complete entries help with data processing and future reference.

Daily Entry

Date: ___________________________

Site: ___________________________

Section: ___________________________

Team: ______________________________________

Weather: ________________________________

Soil conditions: ________________________________

Measurements

Probes deployed: ___________________________

MIT frequencies: ________________________________

ERT baselines: ___________________________

Start time: ______________________

End time: ______________________

Issues encountered: ____

Notes

____

____

____

____

____

____

Completed by: ________________________________

Signature: ________________________________

Date: ______________________

16.7 Quick Reference Summary

Summary of critical items that must be verified at each phase:

Phase	Critical Items	Sign-Off
Pre-Deployment	Permits confirmed Equipment tested Batteries charged Spares packed	■
Site Setup	Grid marked Coordinates recorded Conditions documented	■
Data Collection	Background scan done MIT sweep complete ERT patterns run QC repeats done	■
Post-Survey	Data backed up Equipment cleaned Notes completed	■

Important Notes

- Print multiple copies of this section for field use
- Laminate checklists for durability in wet conditions
- Complete ALL items before moving to next phase
- Document any deviations from standard procedures
- Keep completed logs for project records

Section 17: Application Scenarios

Deployment Configurations for Bomb Craters, Burials, and Wetland Surveys

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

17. Application Scenarios

The HIRT system's modular design enables optimization for diverse field scenarios. This section provides detailed configuration recommendations for three primary application categories: bomb crater investigation, woodland burial search, and wetland/margin surveys. Each scenario requires specific probe lengths, spacing, frequency selection, and deployment strategies to maximize detection probability while maintaining operational safety.

Configuration selection depends on several key factors: target depth, soil conditions, site access constraints, and the nature of expected anomalies. The dual-channel MIT+ERT approach provides complementary information: MIT excels at detecting metallic objects (both ferrous and non-ferrous), while ERT maps soil disturbance patterns, moisture variations, and void structures.

17.1 Scenario 1: Bomb Crater Investigation

Bomb crater investigation represents the most demanding HIRT application, requiring deep penetration (3-4+ meters), comprehensive coverage of disturbed fill material, and detection of potentially large metallic masses. Typical crater dimensions range from 10-15 meters diameter with depths of 2-4 meters.

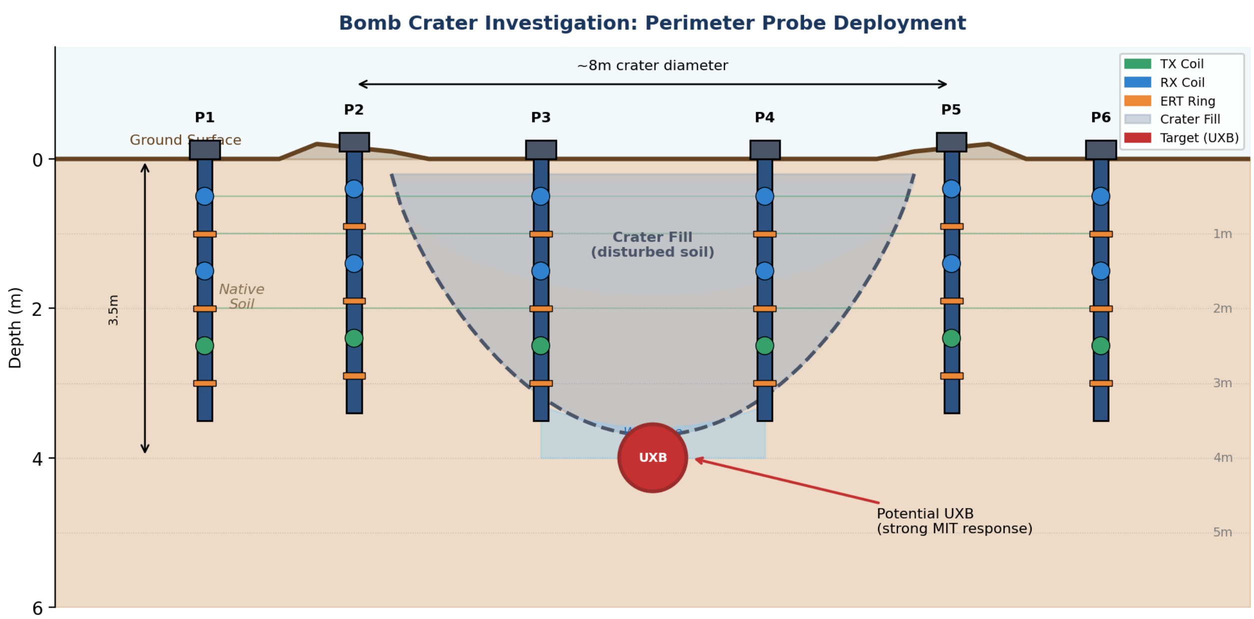


Figure 1. Bomb crater investigation configuration showing perimeter probe deployment around crater margin. Six 3.5m probes at 2m spacing provide comprehensive coverage through crater fill. MIT ray paths (green) interrogate the full volume including potential UXB location at crater base. ERT rings map fill boundaries and wet zones.

Configuration Parameters

- **Rod Length:** 3.0 m (minimum; 3.5m preferred for full-depth coverage)
- **ERT Ring Positions:** 0.5 m, 1.5 m, 2.5 m from probe tip

- **Probe Spacing:** 1.5-2 m between probes
- **Section Size:** Covers full crater plus rim (may require multiple sections)
- **Probe Count:** 20-36 probes depending on crater dimensions

Measurement Strategy

- **MIT Emphasis:** 2-20 kHz frequency range for aluminum/steel mass detection
- **ERT Focus:** Map fill bowl geometry and identify wet pockets
- **Depth Target:** 0-4+ meters (full crater depth plus underlying zone)
- **Frequency Selection:** Lower frequencies (2-5 kHz) for maximum penetration
- **Integration Time:** 10-30 seconds per measurement for improved SNR at depth

Deployment Considerations

Crater investigation presents unique challenges including uneven surface topography, loose fill material, and potential UXO hazards. Initial deployment should focus on the crater rim where stable soil provides secure probe anchoring.

- **Rim-First Approach:** Deploy perimeter probes before attempting center insertion
- **Multiple Overlapping Sections:** Large craters may require 2-3 overlapping arrays
- **Deep Insertion Protocol:** Use pilot rods to verify probe path before full insertion
- **Extended Baselines:** ERT corner-to-corner measurements for deep investigation

Expected Results

MIT measurements will show strong amplitude and phase anomalies from large metallic objects (engine blocks, landing gear, ordnance casings). ERT will map the crater boundary as a resistivity contrast between disturbed fill and native soil. Water accumulation at the crater base appears as low resistivity zones.

17.2 Scenario 2: Woodland Burials

Woodland burial search requires high-resolution detection of relatively shallow targets (0.5-2 m depth) in environments complicated by root systems and organic material. The primary detection mechanism is ERT mapping of disturbed soil zones (grave shafts), supplemented by MIT detection of metallic artifacts.

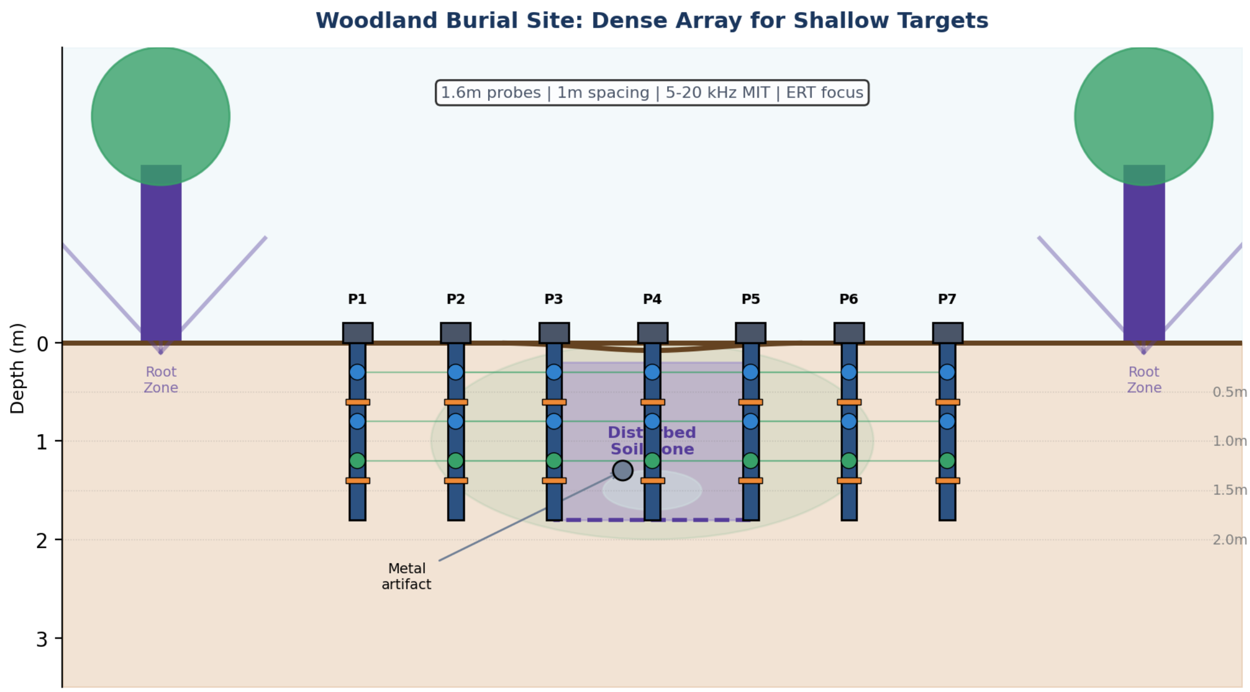


Figure 2. Woodland burial site configuration showing dense probe array (7 probes, 1m spacing) for shallow target detection. Disturbed soil zone (grave shaft) shows distinct ERT contrast. Tree root systems require careful probe positioning. MIT detects small metallic artifacts (buckles, buttons) within burial context.

Configuration Parameters

- **Rod Length:** 1.6 m (sufficient for typical burial depths)
- **ERT Ring Positions:** 0.4 m and 1.2 m from probe tip
- **Probe Spacing:** 1-1.5 m (tight spacing for small targets)
- **Section Size:** 8x8 m standard search area
- **Probe Count:** 12-16 probes for comprehensive coverage

Measurement Strategy

- **ERT Emphasis:** Primary method for grave shaft detection
- **MIT Frequencies:** 5-20 kHz range (focus on small metallic artifacts)
- **Target Signatures:** Clusters of small anomalies suggest artifact concentrations
- **Depth Target:** 0-2 m (standard burial depth range)
- **Multiple Frequencies:** Sweep 5, 10, 20 kHz for sensitivity optimization

Deployment Considerations

Woodland environments require sensitivity to site preservation. Use shallow insertion where possible and avoid major root systems. Document all surface features that may correlate with subsurface anomalies.

- **Minimal Intrusion:** Shallow insertion protocol, narrow pilot holes
- **Root Avoidance:** Survey root positions before probe placement
- **Dense Measurement Pattern:** Short baselines for maximum near-surface resolution
- **Complementary Methods:** Coordinate with GPR surface survey if available

17.3 Scenario 3: Swamp/Wetland Margins

Wetland and swamp margin surveys address the challenge of deep targets (>5 m) in areas with limited access. Probes must be deployed from accessible shore zones, using extended baselines to interrogate central volumes that cannot be directly instrumented.

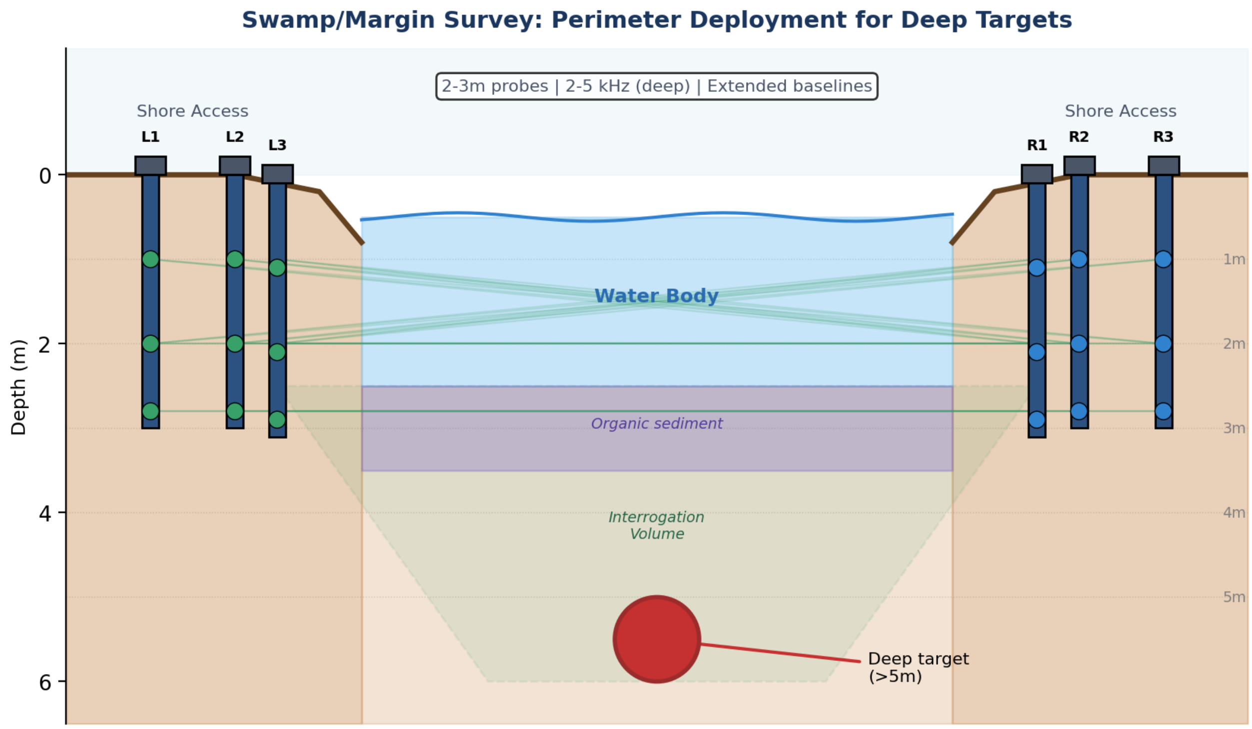


Figure 3. Swamp/margin survey configuration showing shore-based probe deployment. Probes on opposing banks create diagonal ray paths through target volume beneath water body. Low-frequency MIT (2-5 kHz) provides deep penetration. Extended baselines enable detection of targets beyond direct probe reach.

Configuration Parameters

- **Rod Length:** Maximum feasible at margins (typically 1.5-2 m)
- **Probe Spacing:** 2-3 m (wider for challenging access)
- **Section Size:** Adapts to accessible areas
- **Probe Count:** Variable based on margin accessibility
- **Baseline Length:** Maximize TX-RX separation for depth penetration

Measurement Strategy

- **Low MIT Frequencies:** 2-5 kHz for maximum depth penetration
- **Extended Offsets:** Long TX-RX baselines essential for deep targets
- **ERT Configuration:** Wide injection pairs across water if possible
- **Shore-Based Probes:** Deploy from accessible margins only
- **Complementary Methods:** Consider seismic add-on for void detection

Deployment Considerations

Safety is paramount in wetland environments. Ensure stable footing, assess water depth, and use appropriate personal protective equipment. The high conductivity of water affects both MIT and ERT measurements, requiring adjusted interpretation parameters.

- **Access Limitations:** Work strictly from stable shore positions
- **Water Effects:** Account for high conductivity in data interpretation
- **Extended Integration:** Longer measurement times for weak signals
- **Marginal Detection:** Targets near detection limits require repeated measurements

17.4 Scenario Comparison Matrix

The following comparison summarizes key configuration parameters across all three primary scenarios. Selection depends on target depth, soil conditions, and site access constraints.

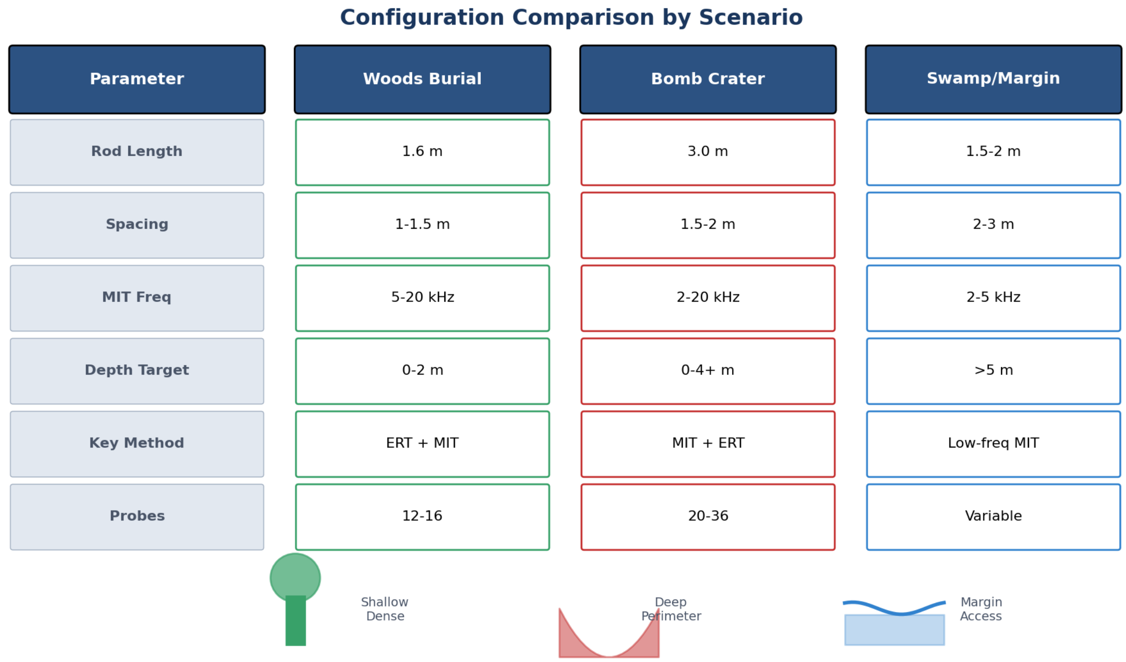


Figure 4. Configuration comparison matrix showing recommended parameters for each scenario. Woods burial uses shallow/dense configuration, bomb crater uses deep/perimeter approach, and swamp/margin requires margin access with extended baselines.

Scenario	Rod Length	Spacing	Frequencies	Depth Target	Key Method
Woods Burials	1.6 m	1-1.5 m	5-20 kHz	0-2 m	ERT + MIT
Bomb Crater	3.0 m	1.5-2 m	2-20 kHz	0-4+ m	MIT + ERT
Swamp/Margins	1.5-2 m	2-3 m	2-5 kHz	>5 m	Low-freq MIT

Table 1. Summary of configuration parameters by application scenario.

17.5 Target Characterization

Understanding expected response patterns helps operators identify and classify anomalies during field operations. The dual-channel MIT+ERT approach provides complementary signatures for different target types.

Figure 5. Target characterization examples showing expected MIT and ERT response patterns. Large metal objects produce strong MIT anomalies; small artifacts show weaker clustered responses. ERT detects fill zones, wet areas, and voids through resistivity contrast. Combined anomalies suggest buried metallic objects in disturbed soil contexts.

Interpretation Guidelines

- **Strong MIT + ERT Contrast:** Large metallic object in disturbed context (e.g., UXB in crater)
- **MIT Only:** Metal object in undisturbed native soil
- **ERT Only:** Soil disturbance without metallic content (possible burial, cache)
- **Weak MIT Cluster:** Multiple small metallic artifacts (artifact scatter)
- **Low ERT Zone:** Water accumulation, saturated fill
- **High ERT Zone:** Air void, dry compacted material

17.6 Site Assessment and Configuration Selection

Proper site assessment is essential for selecting optimal configuration parameters. The decision flow considers target depth, access conditions, soil type, and safety requirements.

Figure 6. Site assessment decision flow for configuration selection. Primary factors include estimated target depth and site access conditions. Secondary considerations include soil conductivity, water table depth, and required resolution. Frequency selection depends on depth requirements and soil conditions.

Pre-Deployment Checklist

1. Conduct site safety assessment (UXO clearance if applicable)
2. Estimate target depth range from historical records or surface features
3. Evaluate access conditions and identify probe deployment zones
4. Assess soil type and expected conductivity
5. Determine required spatial resolution for target detection
6. Select configuration parameters from scenario guidelines
7. Plan grid layout and probe numbering scheme
8. Verify all equipment functionality before deployment

17.7 General Field Procedures

Pre-Deployment

- **Site Assessment:** Evaluate access, safety, and estimated target depth
- **Configuration Selection:** Choose rod length, spacing, and frequencies per scenario

- **Grid Planning:** Lay out probe positions with consistent numbering
- **Equipment Check:** Verify all probes, base hub, tools, and cables

During Deployment

- **Systematic Approach:** Follow 'set once, measure many' workflow
- **Quality Control:** Check reciprocity, repeat critical measurements
- **Documentation:** Record all conditions, anomalies, and deviations
- **Adaptation:** Adjust strategy based on initial results if necessary

Post-Deployment

- **Data Backup:** Secure all data immediately upon completion
- **Quick Analysis:** Generate preliminary plots to verify data quality
- **Equipment Care:** Clean, inspect, and repair probes as needed
- **Documentation:** Complete field notes and measurement logs

17.8 Cost and Timeline Planning

Planning a HIRT deployment requires realistic assessment of equipment costs and build timeline. The following estimates assume standard components and moderate fabrication experience.

Component	Essential (12 probes)	Standard (20 probes)	Complete (24 probes)
Probes	$840-1,800	$1,400-3,000	$1,680-3,600
Base Hub	$200-500	$200-500	$200-500
Tools/Supplies	$200-400	$200-400	$200-400
Total	$1,200-2,700	$1,800-3,900	$2,100-4,500

Table 2. Estimated costs for HIRT system configurations. Actual costs vary by supplier, quantity discounts, and component choices.

Build Timeline

- **Week 1-2 (Prototype):** Build 2 prototype probes, document procedures
- **Week 3 (Calibration):** Bench calibration, test target trials, design refinement
- **Week 4-5 (Scale-up):** Build 12-20 probes, assemble base hub, field shakedown
- **Week 6+ (Deployment):** First real section scans, procedure refinement

17.9 Recommendations

Start Simple

Begin with the core MIT+ERT system on controlled test sites before attempting operational deployments. Build experience with probe handling, measurement protocols, and data interpretation before addressing complex field scenarios.

Add Selectively

Optional enhancements (borehole radar, seismic crosshole, magnetometer sweep) should be added based on demonstrated need rather than theoretical benefit. Each addition increases system complexity and field deployment time.

Maintain Modularity

The modular probe design enables component replacement and configuration adaptation. Maintain this modularity by documenting all modifications and ensuring backward compatibility with existing components.

CRITICAL: UXO SITE SAFETY

- Professional EOD clearance required before ANY probe insertion at suspected UXO sites
- Never hammer or drive probes - use soft insertion only
- Maintain appropriate exclusion zones during all operations
- Monitor groundwater conductivity - elevated levels may indicate corrosion risk
- Document all anomalies for EOD follow-up before excavation

Section 18: Future Development

HIRT Roadmap, Planned Features, and Research Directions

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

18.1 Overview

This document has focused on **hardware and field methods**. The next phase involves **software development** for data processing, inversion, and visualization, as well as continued hardware improvements.

The software development is **explicitly separate** from the hardware/field guide presented in this document. The hardware system is designed to collect high-quality data that can be processed with standard or custom software tools.

18.2 Development Roadmap

The HIRT project follows a phased development approach, with parallel tracks for software and hardware improvements. The timeline below illustrates the planned progression from basic data processing to advanced visualization and machine learning capabilities.

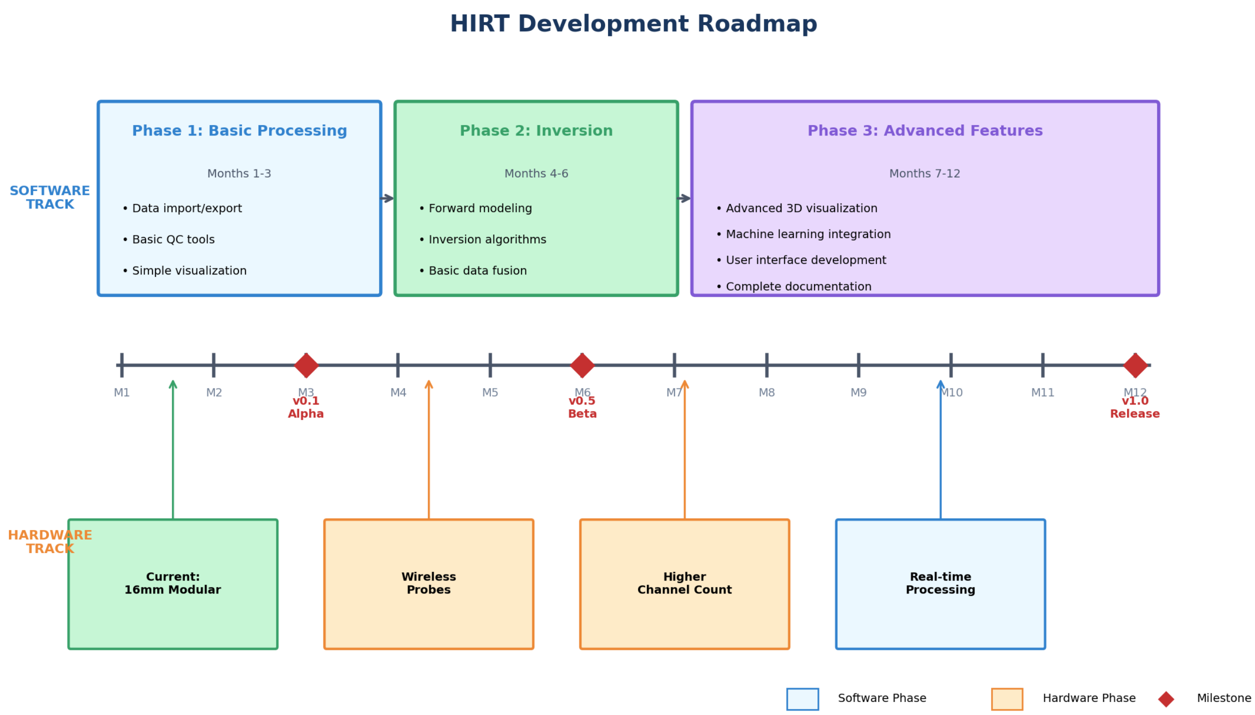


Figure 1. Development roadmap showing software phases (top track) and hardware improvements (bottom track). Key milestones include Alpha (v0.1) at month 3, Beta (v0.5) at month 6, and full Release (v1.0) at month 12.

18.3 Software Development Pipeline

18.3.1 Data QA/QC (Quality Assurance/Quality Control)

The first stage of the processing pipeline involves comprehensive data validation and quality control:

- Import CSV data files with automatic format detection
- Check for missing or corrupted data entries
- Verify reciprocity (A to B approximately equals B to A)
- Remove outliers and flag suspicious measurements for review
- Generate data quality metrics and visualization reports

18.3.2 MIT Inversion

Magnetic Induction Tomography inversion converts amplitude and phase measurements to conductivity distributions:

- Forward modeling: Predict measurements from conductivity model
- Inverse modeling: Reconstruct conductivity from measurements
- Multi-frequency handling for depth resolution
- Regularization for stable, physically meaningful solutions
- Uncertainty quantification for reliability assessment

18.3.3 ERT Inversion

Electrical Resistivity Tomography inversion converts voltage/current measurements to resistivity volumes:

- DC resistivity forward solver (finite element/difference)
- Inversion algorithm with Gauss-Newton or Occam's method
- Electrode position and depth accounting
- Topography handling for non-flat surfaces
- Cross-borehole measurement geometry support

18.3.4 Data Fusion

Combining MIT and ERT data provides complementary information:

- Co-registration of MIT and ERT volumes
- Unified 3D model generation
- Overlay capabilities with GPR, magnetometry, photogrammetry data
- Multi-parameter visualization and interpretation

18.4 Feature Priority Matrix

Features are prioritized based on user impact versus implementation effort. Quick wins (high impact, low effort) receive immediate attention, while major projects are scheduled according to available resources and dependencies.

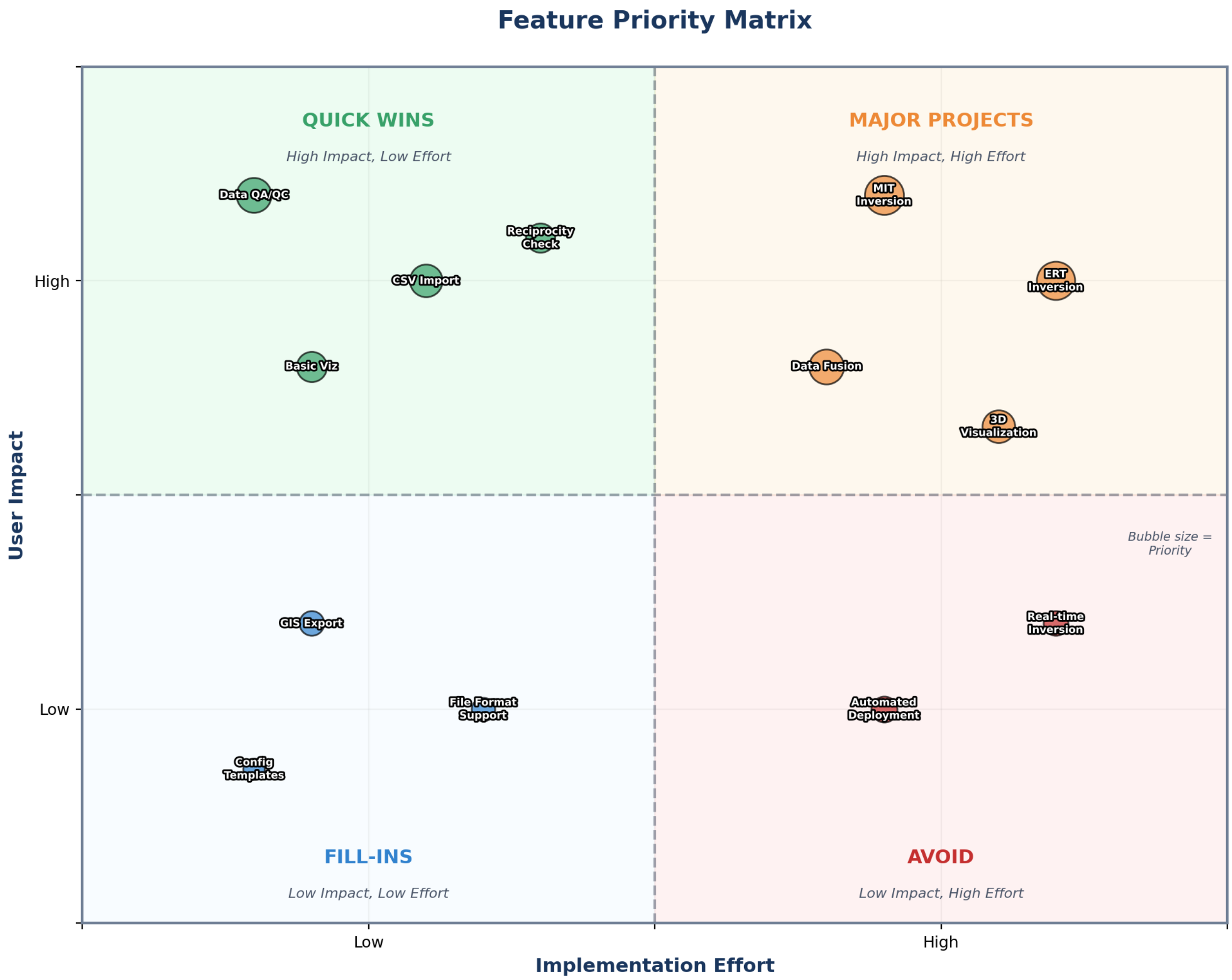


Figure 2. Feature priority matrix categorizing development items by implementation effort (x-axis) and user impact (y-axis). Bubble size indicates relative priority. Quick wins include data QA/QC and basic visualization; major projects include MIT/ERT inversion and 3D visualization.

18.5 Software Architecture

18.5.1 Language and Library Considerations

The software stack is designed for scientific computing efficiency and accessibility:

Language	Strengths	Considerations
Python	Scientific libraries, community support	Primary development language
MATLAB	Powerful, well-documented	Requires license
C++	High performance	Core algorithm optimization
Hybrid	Best of both worlds	Python high-level, C++ intensive computation

Table 1. Language options for software development

18.5.2 Key Libraries and Tools

Library/Tool	Purpose	Notes
NumPy/SciPy	Numerical computing	Foundation for all calculations
VTK/ParaView	3D visualization	Professional rendering
PyVista	Python 3D visualization	VTK wrapper for ease of use
ResIPy/pyGIMLi	ERT inversion	Existing mature tools
SimPEG	EM modeling and inversion	Comprehensive framework

Table 2. Recommended libraries and tools for HIRT software

18.6 Hardware Evolution

The HIRT probe design has evolved through three major versions, each addressing lessons learned from field testing and user feedback. The current v3.0 16mm Modular design represents a balance between minimal site disturbance and mechanical durability.

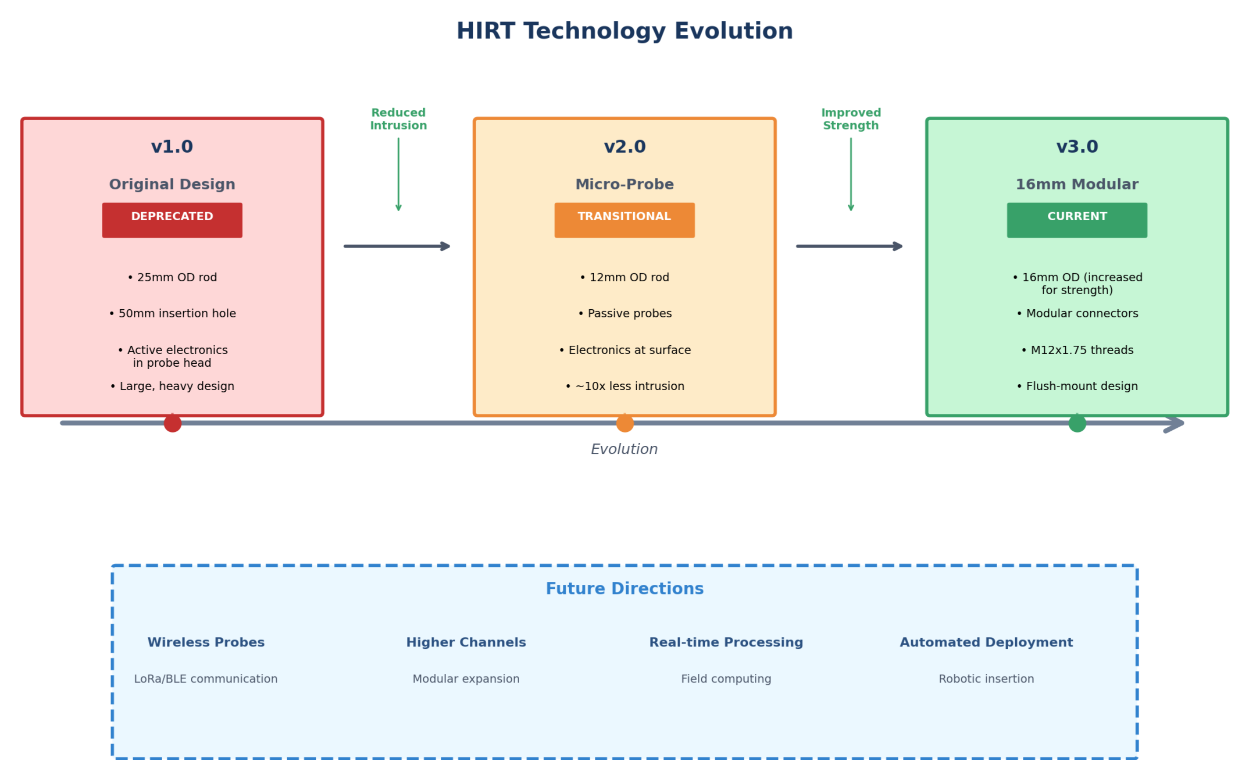


Figure 3. Technology evolution from v1.0 (25mm active probe) through v2.0 (12mm passive) to the current v3.0 (16mm modular). Key improvements include reduced intrusion, increased strength, and modular field serviceability. Future directions include wireless communication and real-time processing.

18.7 Planned Hardware Improvements

18.7.1 Wireless Probes

Wireless communication would significantly reduce cable management complexity and enable faster deployment:

- LoRa or BLE communication protocols under evaluation
- Balance power consumption versus convenience
- Maintain data integrity and timing synchronization
- Consider field-replaceable battery modules

18.7.2 Higher Channel Count

- Increased probe density for finer resolution
- Modular expansion through daisy-chaining
- Enhanced multiplexing architecture
- Scalable from 4 to 16+ probes

18.7.3 Real-time Processing

- Process data during collection
- Enable adaptive survey strategies
- Immediate quality feedback in the field
- Requires edge computing capability (e.g., Raspberry Pi, Jetson)

18.8 Forward Modeling and Validation

Before field deployment, the HIRT system response should be validated using synthetic models. Recommended tools include:

Tool	Focus	Strengths	URL
SimPEG	MIT + ERT	Full forward/inverse modeling, Python	simpeg.xyz
pyGIMLi	ERT-focused	Excellent visualization, mature	pygimli.org
Empymod	1D layered EM	Fast, accurate for stratified media	empymod.emsig.xyz

Table 3. Recommended forward modeling tools

18.8.1 Standard Validation Scenarios

Four standard scenarios are recommended for system validation:

1. **Aluminum Bomb in Sandy Loam:** 1m diameter sphere at 3m depth in 0.1 S/m soil - validates MIT response to non-ferrous UXO
2. **Grave Shaft (Disturbed Fill):** 0.8x0.5x1.5m prism with 0.05 S/m fill in 0.2 S/m clay - validates ERT contrast detection
3. **Scattered Aircraft Debris:** Multiple fragments (0.2-1m) at 1-4m depths - validates MIT multi-target discrimination
4. **Bomb Crater with Heterogeneous Fill:** 8m diameter, 5m deep crater with variable conductivity - tests combined MIT+ERT response

18.9 Known Limitations

Technical Limitations

- Smaller coil area results in ~19 dB SNR loss (compensated by longer integration)
- Survey time increases 5-10x compared to commercial systems
- Post-processing software required for 3D reconstruction
- Limited depth penetration in highly conductive soils

Current System Constraints

- Electronics SNR adequate for detection but compromised for precise characterization
- Phase accuracy: +/-5 degrees (vs. commercial +/-0.5 degrees)
- Noise floor: ~100 nV (vs. commercial ~10 nV)

18.10 Manufacturing Status

The current release (16mm Modular Probe, released 2024-12-19) is ready for production printing. The design follows the philosophy of 'archaeologist brain first, engineer brain second' - minimizing site intrusion while maintaining field serviceability.

Component	Status	Notes
Male Insert Plug	Ready	Tested, verified
Female Sensor Module	Ready	Tested, verified
Probe Tip	Ready	Tested, verified
Top Cap	Ready	Tested, verified
ERT Ring Collar	Ready	Tested, verified
Rod Coupler	Ready	Tested, verified
Base Hub Enclosure	In Progress	Backplane PCB design
Cable Harness	Specified	Ready for fabrication

Table 4. Component manufacturing status

18.11 Machine Learning Opportunities

Machine learning presents opportunities for automated analysis and interpretation:

- **Anomaly detection:** Automatically identify targets of interest
- **Classification:** Distinguish metal vs. void vs. disturbed soil
- **Quality assessment:** Predict data quality from acquisition parameters
- **Parameter estimation:** Estimate target properties (size, depth, conductivity)

Machine learning integration requires labeled training data from both synthetic forward models and validated field measurements.

18.12 Documentation Needs

18.12.1 User Documentation

- Processing workflow guide with step-by-step instructions
- Parameter selection guidelines for different survey types
- Interpretation guide with example datasets
- Troubleshooting common issues

18.12.2 Technical Documentation

- Algorithm descriptions with mathematical derivations
- Code documentation (docstrings, API reference)
- Validation studies with synthetic and field data
- Performance benchmarks for different hardware configurations

Section 19: Ethics, Legal, and Safety

Safety Protocols for UXO Sites, Legal Compliance, and Ethical Guidelines

Version: 2.0 | **Date:** January 2026 | **HIRT Whitepaper**

19.1 Introduction

HIRT deployment at sensitive archaeological, forensic, or humanitarian demining sites requires strict adherence to safety protocols, legal requirements, and ethical guidelines. This section provides comprehensive guidance for safe and responsible operations, with particular emphasis on unexploded ordnance (UXO) site safety.

19.2 Human Remains Protocol

HIRT surveys at sites potentially containing human remains must be treated as **forensic/archaeological contexts**. The following requirements apply:

- Obtain all **permits and permissions** before deployment
- Follow jurisdictional requirements (heritage boards, war graves authorities)
- Maintain proper chain of custody for any findings
- Document all activities thoroughly with photographs and written records
- Coordinate with relevant authorities before, during, and after surveys

19.3 UXO Risk Assessment

CRITICAL WARNING

- WWII sites can contain live ordnance
- Standard insertion methodology is DANGEROUS at UXO sites
- Never drive or hammer probes until area is cleared by qualified EOD/UXO professionals

19.3.1 Pre-Survey Requirements

Before any HIRT deployment at a suspected UXO site, the following requirements must be satisfied:

1. Coordinate with explosive ordnance disposal (EOD) teams
2. Obtain professional EOD sweep clearance for the survey area
3. Follow established UXO clearance protocols for the jurisdiction
4. Maintain safe standoff distances during all operations
5. Establish clear emergency evacuation procedures

19.3.2 Critical Problems with Standard Procedures

The standard HIRT insertion methodology ("drive pilot rod to depth, wiggle to 12-14 mm, remove") presents unacceptable risks at UXO sites:

- **Mechanical trigger risk:** Driving a steel rod into ground containing potential ordnance could trigger detonation

• **No risk analysis:** Standard procedures lack risk analysis for probe insertion near UXB
• **Electrical interaction:** ERT current injection (0.5-2 mA) could theoretically interact with sensitive fuzes
• **Transient hazards:** No overvoltage protection specified (12V/0.5 ohm = 24A transient on short)

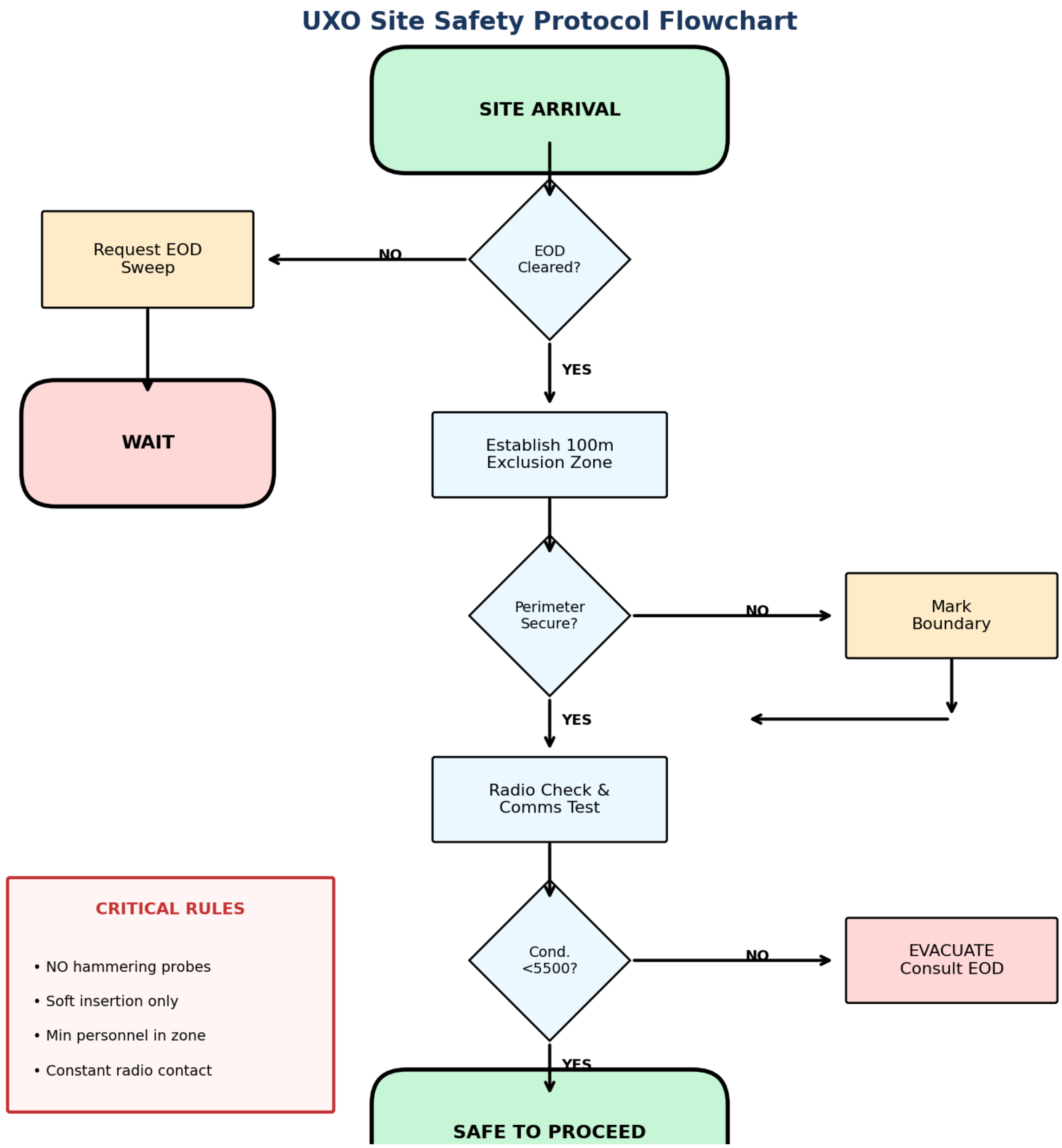


Figure 1. UXO site safety protocol decision flowchart. Each survey must complete all safety checks before proceeding with probe insertion.

19.3.3 Required Safety Measures for UXO Sites

Protocol	Action
Pre-survey EOD clearance	Professional EOD sweep before ANY insertion
Safe standoff perimeter	Minimum 100m exclusion zone during insertion
Soft insertion only	Hand auger or water-jet only (NO hammering)
Conductivity pre-check	Check soil conductivity before deep insertion
Personnel limits	Minimum personnel in hazard zone
Communications	Constant radio contact with safe zone

Table 1. Required safety measures for UXO site operations

19.4 Conductivity Threshold Monitoring

Research (Waga et al. 2026) indicates that conductivity >6,000 uS/cm at WWII bomb craters signals chemical activation risk, potentially leading to spontaneous explosions. HIRT's ERT-Lite system provides continuous conductivity monitoring capability.

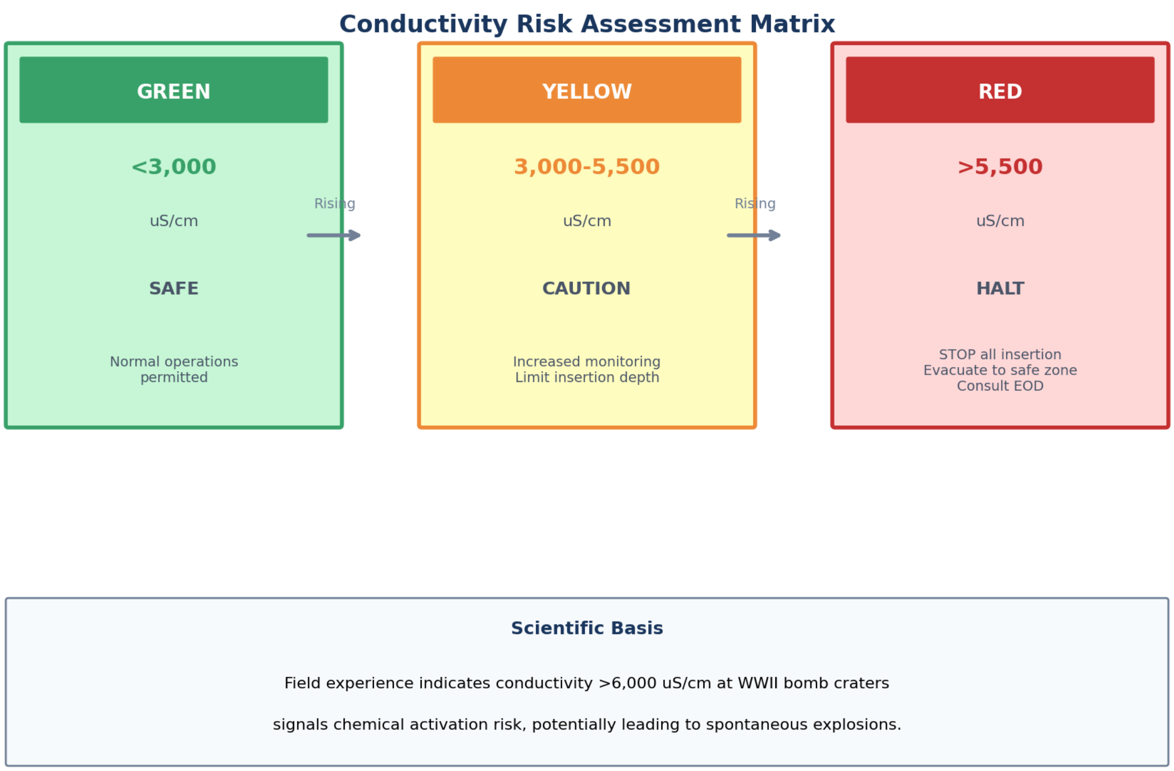


Figure 2. Conductivity-based risk assessment matrix. Operations must halt immediately if conductivity exceeds 5,500 uS/cm.

19.4.1 Safety Thresholds

Conductivity	Status	Action
<3,000 uS/cm	GREEN (Safe)	Normal operations
3,000-5,500 uS/cm	YELLOW (Caution)	Increased monitoring, limit insertion depth
>5,500 uS/cm	RED (Halt)	STOP all insertion, evacuate to safe zone, consult EOD

Table 2. Conductivity safety thresholds for UXO site operations

19.4.2 Time-Lapse Monitoring Schedule

For extended UXO site investigations, implement the following monitoring schedule:

Phase	Timing	Metrics	Action
Baseline	Day 0	Full MIT + ERT survey	Establish reference values
Early detection	Day 7-14	Conductivity only	Alert if >10% change
Long-term	Monthly	Full ERT	Track redox boundary evolution
Pre-excavation	24-48h before	Full survey	Final safety check

Table 3. Recommended time-lapse monitoring schedule for UXO sites

19.5 Rim-Only Deployment

For craters with suspected UXB at center, deploy probes **around the perimeter only**. This approach maintains survey geometry while avoiding direct insertion over suspected ordnance.

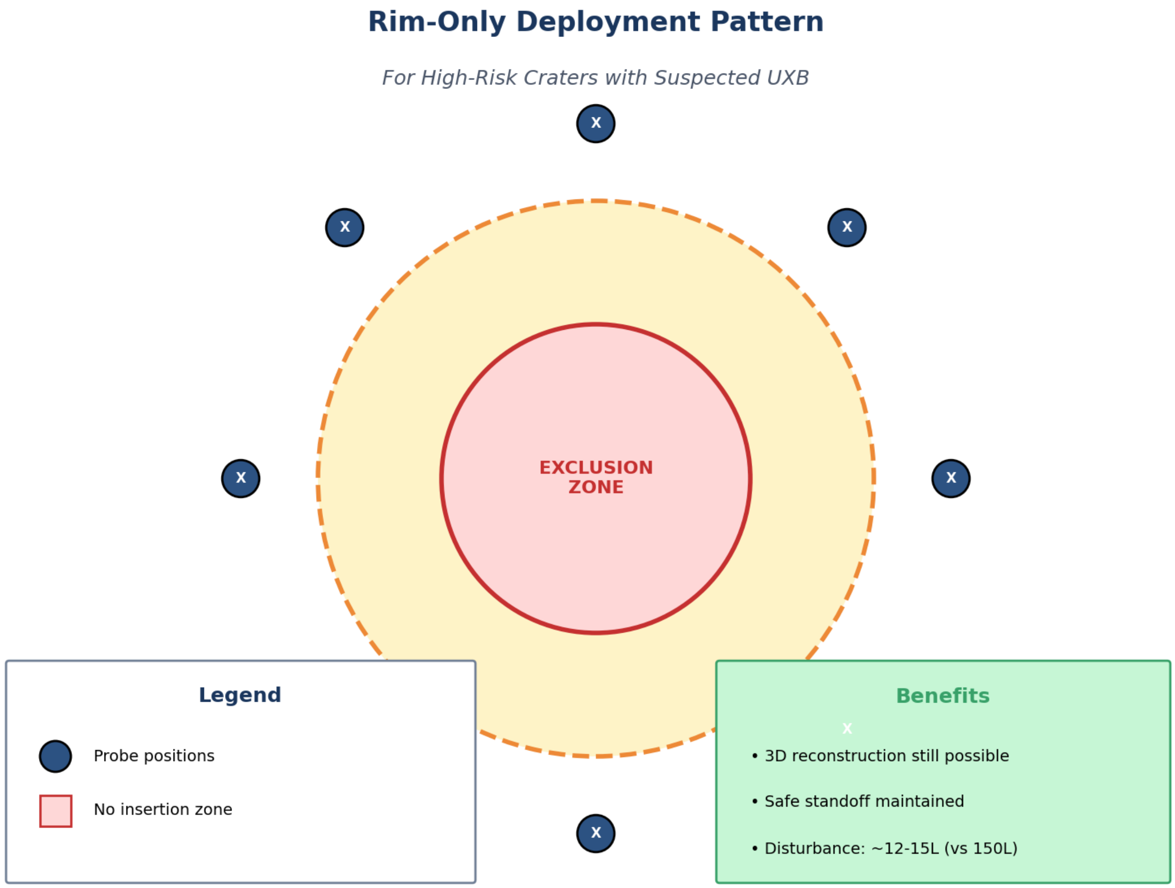


Figure 3. Rim-only deployment pattern for high-risk craters. Probes are positioned around the perimeter, maintaining safe standoff from the central exclusion zone.

HIRT Early Warning Capability

- Volumetric 3D resistivity (vs. single-point measurements)
- Gradient detection identifies active redox boundaries
- Non-magnetic operation safe near UXB
- "Set Once; Measure Many" enables time-lapse without repeated insertion

19.6 Minimal Intrusion Principles

HIRT operations should always prioritize minimal site disturbance. The following principles guide responsible deployment:

- Prefer **rim/perimeter probing** over direct insertion into suspected areas
- Use **shallow depths** when possible to achieve survey objectives
- Employ **pilot holes** to minimize ground disturbance volume

- **Avoid inserting probes into suspected burial voids** without explicit authorization
- Document all probe insertion points and depths for site records

19.7 Field Safety Checklist

The following checklist must be completed before commencing any HIRT survey at a UXO-suspected site. All critical items (marked with a star) are mandatory.

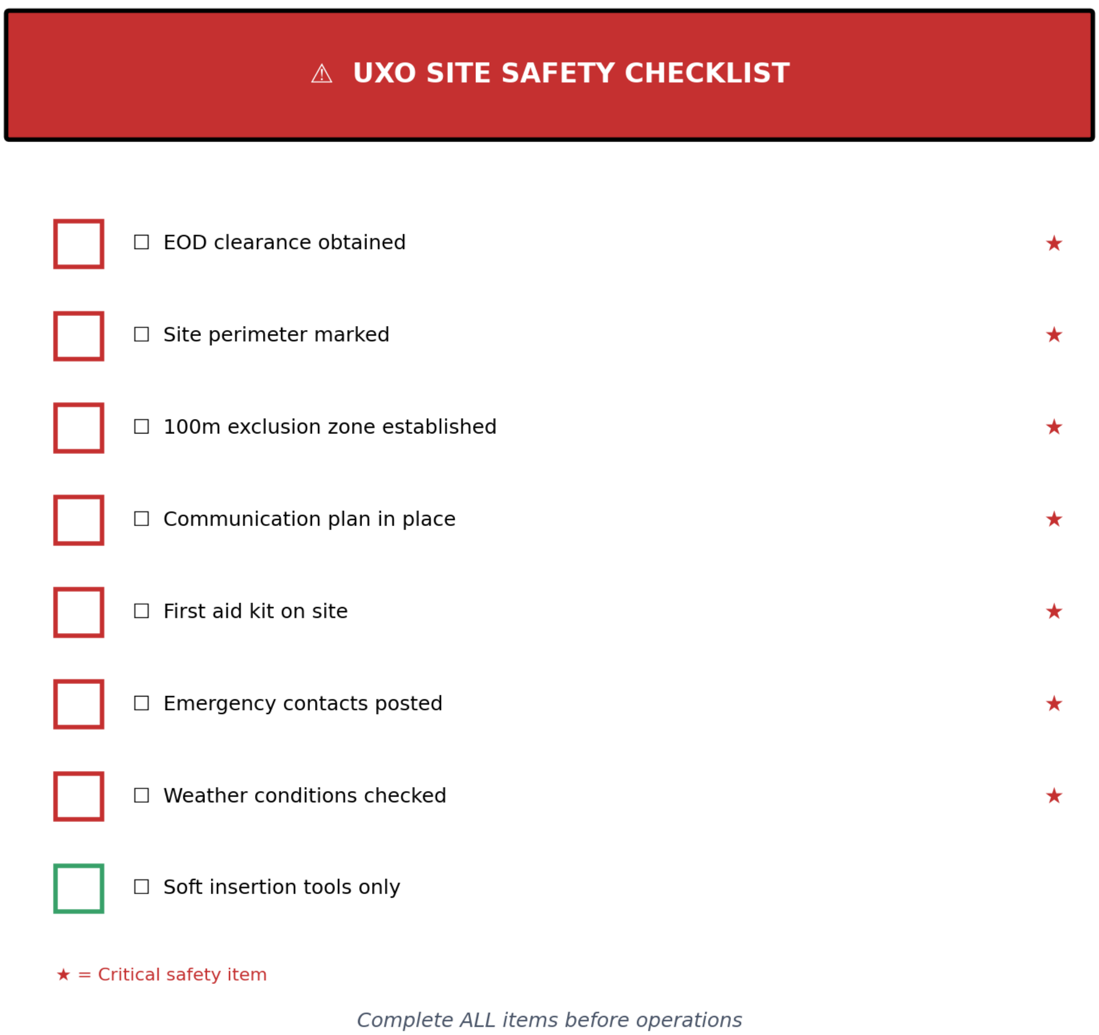


Figure 4. UXO site safety checklist. All critical items (marked with star) must be verified before operations commence.

19.8 General Field Safety

Beyond UXO-specific protocols, all HIRT field operations must adhere to general safety practices:

- Maintain clear communication protocols between all team members
- Use appropriate personal protective equipment (PPE) for site conditions
- Have emergency contact information readily available and posted
- Follow local environmental regulations for equipment deployment

- Respect site boundaries and access restrictions at all times
- Conduct daily equipment safety checks before deployment
- Maintain first aid kit and emergency supplies on site

19.9 Summary: Recommended Protocol

For UXO sites requiring time-lapse monitoring, implement the following protocol:

1. Baseline ERT survey of crater perimeter (Day 0)
2. Weekly monitoring of conductivity trends
3. Alert threshold set at >10% change from baseline
4. Halt excavation immediately at >5,500 uS/cm
5. Consult EOD team for any anomalous readings

References

[1] OSCE Guidelines for Humanitarian Demining Operations (2024). Organization for Security and Co-operation in Europe.

[2] IMAS 07.11: Land Release. International Mine Action Standards, 3rd Edition (2023).

[3] ASTM D7128-18: Standard Guide for Using the Seismic-Reflection Method for Shallow Subsurface Investigation.

[4] US Army Corps of Engineers (2018). Engineering and Design: Ordnance and Explosives Response. EM 200-1-15.