HIRT: Hybrid Inductive-Resistivity Tomography

Technical Manual

HIRT Development Team

2026-02-01

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2 Welcome to HIRT

HIRT (Hybrid Inductive-Resistivity Tomography) is a dual-channel subsurface imaging system designed for archaeological, forensic, and environmental investigations. By combining magneto-inductive (MIT-3D) and electrical resistivity (ERT-Lite) tomography in a crosshole configuration, HIRT achieves true 3D imaging of subsurface features at depths where surface methods fail.

This technical manual provides complete documentation for building, operating, and understanding the HIRT system.

2.1 Who Is This Manual For?

This documentation follows an "onion model"—start from the layer that matches your needs:

2.1.1 Field Operators

Start here: Field Guide

You have a working HIRT system and need to conduct surveys. The Field Guide covers deployment, data acquisition, interpretation, and troubleshooting without requiring deep technical knowledge.

2.1.2 Builders

Start here: Build Guide

You want to construct a HIRT system. The Build Guide provides complete bills of materials, mechanical design, electronics, assembly procedures, and testing/validation protocols.

2.1.3 Researchers and Students

Start here: Theory

You want to understand the physics, algorithms, and design decisions behind HIRT. The Theory section covers electromagnetic induction, resistivity tomography, inversion mathematics, and multi-modal fusion.

2.1.4 Developers

Start here: Developer Guide

You want to contribute code, improve firmware, or extend HIRT capabilities. The Developer Guide covers data formats, firmware architecture, and the project roadmap.

2.2 Quick Navigation

I want to...	Go to...
Learn what HIRT does	Overview
Understand safety requirements	Safety
Deploy probes and collect data	Deployment
Interpret survey results	Interpretation
Order parts and build a system	Bill of Materials
Understand the physics	Physics Theory
Learn about sensor options	Sensor Modalities
Contribute to the project	Contributing
Look up a term	Glossary

2.3 Cross-Cutting Concerns

Some topics span multiple layers. Use these links when your question crosses boundaries:

Troubleshooting: If a problem occurs in the field, start with Field Troubleshooting. If you suspect a build issue, see Testing & Verification. For theory behind the symptoms, check Uncertainty & Limitations.

Calibration: Field operators should follow Field Calibration procedures. Builders should understand Testing & Verification before delivery. Theory users can find calibration mathematics in Inversion.

Data Formats: For recording data in the field, see Data Acquisition. For file specifications and software compatibility, see Data Formats.

2.4 System Overview

HIRT uses two complementary sensing channels:

MIT-3D (Magneto-Inductive Tomography): Low-frequency TX/RX coils (2-50 kHz) detect metallic objects, including non-ferrous metals like aluminum that are invisible to magnetometers.

ERT-Lite (Electrical Resistivity Tomography): Ring electrodes inject small currents (0.5-2 mA) to map soil disturbance, moisture content, and resistivity contrasts.

The crosshole geometry—with probes inserted into the ground—provides direct ray paths through the target volume, achieving 2-5× better resolution than surface methods at depths beyond 2 meters (*modeled estimate; field validation pending*).

2.4.1 Primary Applications

- **Filled bomb crater investigation:** UXO, remains, structural debris
- **Forest burial detection:** Clandestine graves, historical burials
- **Crash site recovery:** Aircraft wreckage in challenging terrain
- **Environmental assessment:** Contamination plumes, buried waste

2.5 Documentation Standards

This manual uses consistent terminology and formatting:

- **Specifications** are qualified as *Measured*, *Modeled*, or *Target*
- **MIT-3D** refers to the inductive channel (not "EMI" or "metal detector")
- **ERT-Lite** refers to the resistivity channel (not "galvanic")
- **Crosshole** describes the measurement geometry
- Units follow SI conventions with space between value and unit (e.g., "16 mm")

See the Glossary for complete terminology.

2.6 Project Status

HIRT is open-source scientific hardware under active development. Current status:

- **Hardware design:** Mature (revision 2.3)
- **Build documentation:** Complete
- **Field validation:** Ongoing
- **Software tools:** In development

For the latest status and roadmap, see Developer: Roadmap.

2.7 Getting Help

- **Issues and questions:** GitHub Issues
- **Contribution guidelines:** Contributing
- **License:** This documentation and hardware designs are released under open-source licenses. See the repository for details.

Part I
Getting Started

3 Overview

3.1 What is HIRT?

HIRT (Hybrid Inductive-Resistivity Tomography) is a **dual-channel subsurface 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.

3.2 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.

3.3 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.

i 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)

3.4 Primary Use Cases

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

Table 2: *Primary HIRT use cases and configurations*

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/Marsh Crash	5-8+m depth; 3.5m probes, 2-3m spacing	Low-freq MIT	Deep-buried aircraft

3.5 System Capabilities

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 (*modeled*)
- **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

3.6 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.

3.7 Optimal Workflow

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.

3.8 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

3.9 Cost Overview

Table 3: *HIRT system cost breakdown*

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

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.

4 Quick Start

4.1 Overview

This quick start guide walks you through your first HIRT survey, from equipment check to data collection. For detailed procedures, see the Field Guide.

4.2 Before You Begin

Ensure you have:

- ☐ Complete HIRT probe set (minimum 4 probes for basic survey)
- ☐ Zone hub and cables
- ☐ Data acquisition unit (laptop or dedicated controller)
- ☐ Pilot rod for hole preparation
- ☐ Soft mallet or hand auger
- ☐ Measuring tape and grid markers
- ☐ Field notebook or recording forms

> ⚠ Safety First
>
> Review Safety Requirements before any field work. At UXO-suspected sites, EOD clearance is mandatory before probe insertion.

4.3 Step 1: Site Assessment (15-30 minutes)

1. **Survey the area** for obstacles, utilities, and access constraints
2. **Mark grid positions** using tape measure and markers
3. **Document conditions** including soil type, moisture, and vegetation
4. **Photograph the site** before any disturbance

4.4 Step 2: Grid Layout

Standard configurations:

Grid	Probe Count	Coverage	Best For
2×2	4	Small area (4 m^2)	Single target localization
3×3	9	Medium area (16 m^2)	Standard investigation
4×4	16	Large area (36 m^2)	Comprehensive survey

Choose probe spacing based on required resolution:

- **1.0 m spacing:** High resolution, small features
- **1.5 m spacing:** Standard balance of resolution and coverage
- **2.0 m spacing:** Rapid reconnaissance, large features

4.5 Step 3: Probe Insertion (5-10 minutes per probe)

1. **Create pilot hole** using auger or pilot rod
   - Target diameter: 12-14 mm (slightly larger than probe)
   - Target depth: Match probe length (typically 1.5-3.0 m)
2. **Insert probe** by hand
   - Maintain vertical orientation
   - Note any obstructions (record actual depth achieved)
3. **Document position**
   - Record X, Y coordinates from grid origin
   - Record actual insertion depth (z_tip_m)
   - Note any offset from ideal position
4. **Connect cables** to zone hub
   - Verify secure connection at both ends
   - Route cables to avoid trip hazards

4.6 Step 4: System Initialization (5 minutes)

1. **Power on** the zone hub and data acquisition unit
2. **Run self-test** to verify all probes respond

3. **Check connection quality** (all probes should show green status)
4. **Record baseline** ambient readings

4.7 Step 5: Data Acquisition (15-45 minutes)

1. **Start measurement cycle**
   - MIT sweep: 2 kHz –> 10 kHz –> 50 kHz
   - ERT injection: Standard pattern
2. **Monitor acquisition**
   - Watch for error indicators
   - Note any unusual readings
3. **Quality check**
   - Verify reciprocity (A to B should approximately equal B to A)
   - Check for drift between first and last measurements
4. **Record metadata**
   - Start/end times
   - Weather conditions
   - Personnel present

4.8 Step 6: Data Export and Backup

1. **Export CSV files** for MIT and ERT data
2. **Copy to backup media** (SD card, USB drive)
3. **Verify file integrity** (open and check record counts)
4. **Complete field notes** while details are fresh

4.9 Step 7: Probe Extraction

1. **Disconnect cables** from zone hub
2. **Extract probes** by pulling straight up
3. **Clean probes** and inspect for damage
4. **Fill holes** if site protocol requires
5. **Restore site** to original condition

4.10 Quick Reference: Typical Workflow

Phase	Duration	Key Actions
Setup	30-60 min	Grid layout, probe insertion
Acquisition	15-45 min	MIT + ERT measurement cycles
QA/QC	10-15 min	Reciprocity check, backup
Extraction	20-40 min	Probe removal, site restoration
Total	**1.5-3 hours**	For 4×4 grid (16 probes)

4.11 Next Steps

After your first survey:

1. **Review data quality** using the Interpretation Guide
2. **Process data** with inversion software (see Theory: Inversion)
3. **Document findings** for reporting

4.12 Common Issues

Problem	Quick Fix
Probe won't insert	Use auger to clear obstruction, don't force
Connection error	Clean connectors, check cable routing
Noisy data	Move away from power lines, pause for passing vehicles
Poor reciprocity	Check electrode contact, may need conductive gel

For detailed troubleshooting, see Field Troubleshooting.

5 Safety

5.1 Overview

HIRT deployment at sensitive archaeological, forensic, or humanitarian demining sites requires strict adherence to safety protocols. This section provides essential safety guidance for field operations. For detailed legal and regulatory requirements, see Appendix: Regulations.

5.2 General Field Safety

All HIRT field operations must adhere to these 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

5.3 Human Remains Protocol

HIRT surveys at sites potentially containing human remains must be treated as **forensic/archaeological contexts**:

- 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

5.4 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

5.4.1 Pre-Survey Requirements

Before any HIRT deployment at a suspected UXO site:

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

5.4.2 Active Signal Safety (HERO Protocols)

The HIRT system operates in the 2-50 kHz range, classifying it as an active emitter under **HERO (Hazards of Electromagnetic Radiation to Ordnance)** standards.

The Risk: The 2-50 kHz AC signal can induce eddy currents in **Electro-Explosive Devices (EEDs)** found in some German and Allied bombs.

Required Protocol:

1. **Treat as HERO UNSAFE:** Until specific ordnance types are ruled out, assume the probe's electromagnetic field can trigger EEDs
2. **Passive Scan First:** Use magnetometer sensors *passively* (MIT transmitter OFF) to scan the look-ahead buffer (1.5-2.0 meters)
3. **Clearance:** Only activate the MIT transmitter once the immediate volume is confirmed clear of ferrous anomalies

5.4.3 Required Safety Measures for UXO Sites

Table 7: *Required safety measures for UXO site operations*

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

5.4.4 Critical Problems with Standard Procedures

The standard HIRT insertion methodology 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 could theoretically interact with sensitive fuzes

5.5 Conductivity Threshold Monitoring

Research indicates that conductivity >6,000 uS/cm at WWII bomb craters signals chemical activation risk. HIRT's ERT-Lite system provides continuous conductivity monitoring capability.

5.5.1 Safety Thresholds

Table 8: *Conductivity safety thresholds for UXO site operations*

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

5.5.2 Time-Lapse Monitoring Schedule

For extended UXO site investigations:

Table 9: *Recommended time-lapse 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

5.6 Rim-Only Deployment

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

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

5.7 Minimal Intrusion Principles

HIRT operations should always prioritize minimal site disturbance:

- 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

5.8 Field Safety Checklist

Complete this checklist before commencing any HIRT survey at a UXO-suspected site. All critical items (marked with *) are mandatory.

Table 10: *UXO site safety checklist*

Item	Critical	Status
* EOD professional clearance obtained	Yes	[ ]
* Emergency evacuation plan established	Yes	[ ]
* Radio communication verified	Yes	[ ]
* Safe zone perimeter marked (100m+)	Yes	[ ]
Weather conditions acceptable	No	[ ]
* Conductivity baseline <3000 uS/cm	Yes	[ ]
Equipment safety check complete	No	[ ]
* Minimum personnel in hazard zone	Yes	[ ]
Site documentation prepared	No	[ ]
* EOD contact on standby	Yes	[ ]

5.9 Summary: Recommended Protocol

For UXO sites requiring time-lapse monitoring:

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

Part II
Field Guide

6 Deployment

6.1 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.

6.2 Pre-Deployment Planning

6.2.1 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.

6.2.2 Equipment Checklist

Table 11: *Field equipment checklist for HIRT deployment*

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

6.3 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.

Table 12: *Standard grid configurations for different survey scenarios*

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

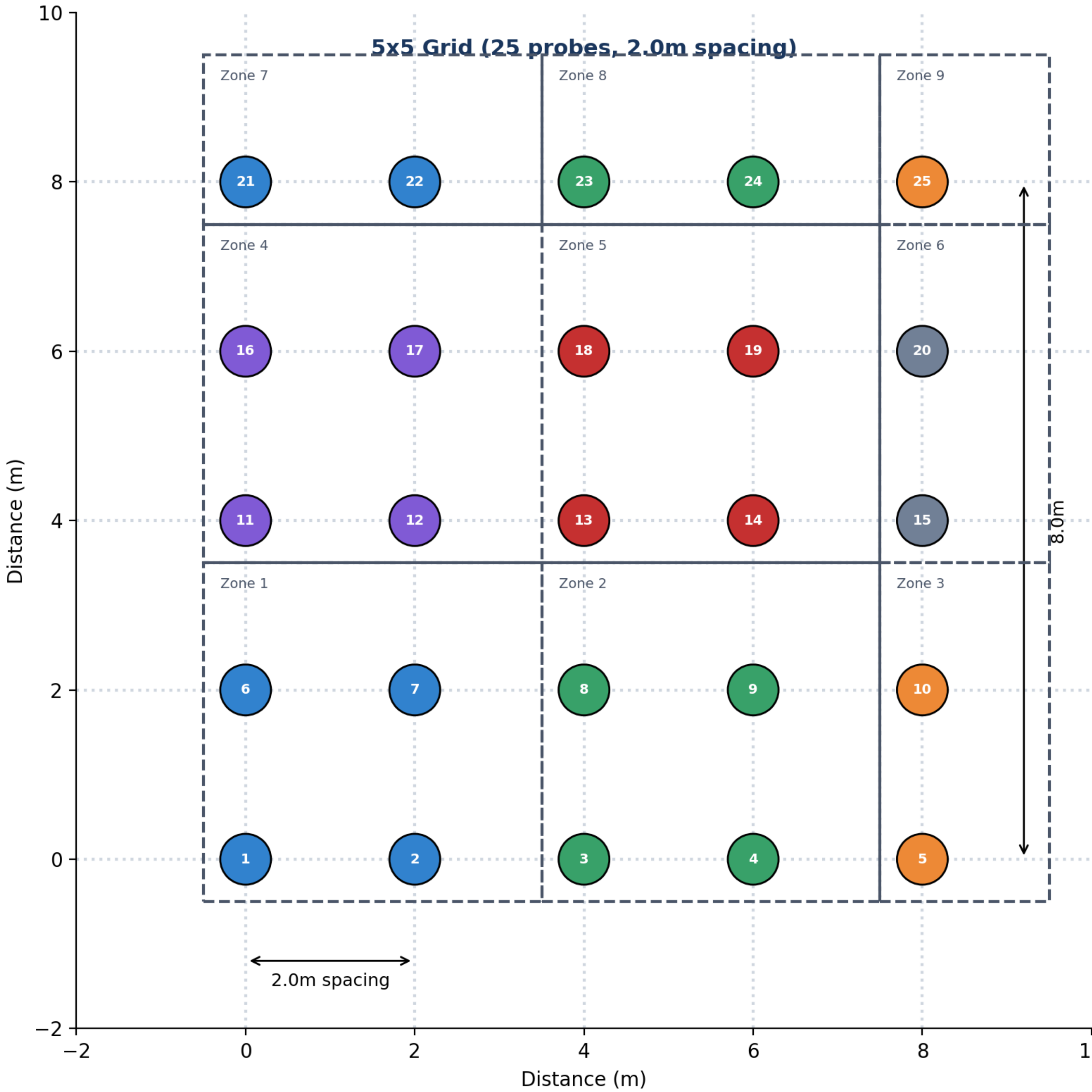

Figure 1: *Standard 10x10 m grid layout with 2 m probe spacing showing zone groupings for sequential deployment. Probes are numbered 1-25 in row-major order.*

6.3.1 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.

6.4 Probe Installation

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

Table 13: *Recommended insertion depths by survey scenario*

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

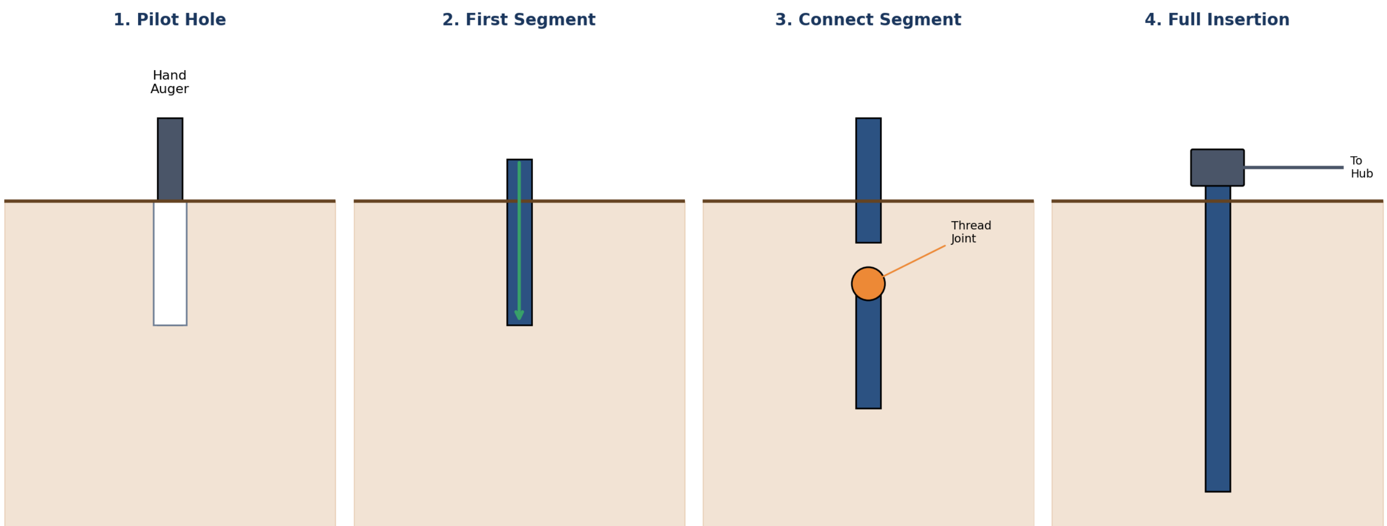

Figure 2: *Probe insertion procedure showing the four-step process: (1) pilot hole creation with hand auger, (2) first segment insertion, (3) segment connection at thread joint, and (4) completed installation with junction box and cable routing.*

6.4.1 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

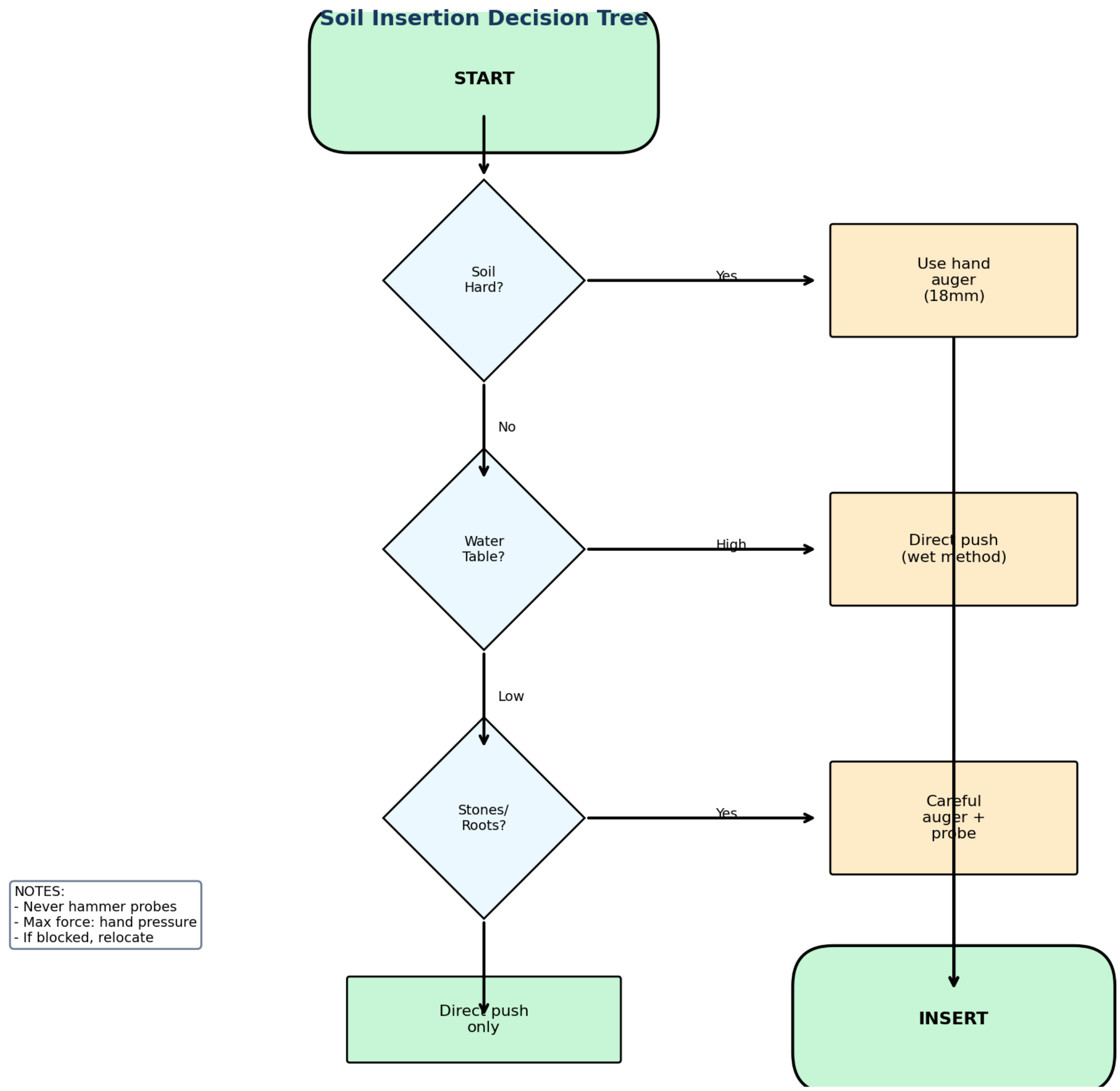

Figure 3: *Soil type insertion decision tree. The procedure adapts based on soil hardness, water table depth, and presence of obstructions. Key principle: never hammer probes; use maximum hand pressure only.*

- May need to relocate probe position slightly

i 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

6.4.2 Cable Length and Signal Integrity

The HIRT system uses **passive probes** with all active electronics in the central hub. This architecture offers cost and reliability advantages but requires attention to cable length effects on MIT receive signals, which operate in the microvolt range.

The Signal Integrity Challenge: MIT RX coils produce signals of approximately 1 μV at the probe. These signals must travel through the probe cable (3-5 m) and trunk cable (variable length to hub) before reaching the preamplifier. Cable capacitance creates a low-pass filter effect, and longer cables increase susceptibility to electromagnetic interference (EMI) pickup.

Table 14: *Cable length impact on MIT signal integrity.*

Trunk Cable Length	Signal Degradation	EMI Susceptibility	Recommendation
<5 m	<10%	Low	Passive probes OK
5-10 m	10-25%	Moderate	Passive probes OK with shielding
10-15 m	25-40%	High	Consider active probe option
>15 m	>40%	Very High	Active probes recommended

Cable Capacitance Effect: Typical shielded cable has capacitance of approximately 100 pF/m. A 20 m cable run creates ~2 nF capacitive load. At 20 kHz operating frequency, this represents an impedance of ~4 k-ohm—significant for microvolt-level signals driving typical coil source impedances.

Practical Guidelines:

- **Standard deployments (10 m total cable run):** Passive probes provide adequate SNR with no additional measures beyond standard shielded cable
- **Extended deployments (10-15 m):** Use low-capacitance cable, minimize parallel cable runs, ensure single-point shield grounding
- **Large-area surveys (>15 m):** Consider the **optional active probe** configuration (adds $50-80/probe) which places a unity-gain buffer at the probe, driving the cable with a low-impedance source

Field Tip: Testing Cable Length Impact

Before committing to a large deployment, verify acceptable SNR at your planned cable lengths. Set up a single probe at the maximum expected distance from the hub and measure noise floor with TX disabled. If the noise exceeds 500 nV RMS, consider active probes or repositioning the hub closer to the probe array.

6.5 Cable Management and Field Logistics

Managing cable harnesses for 16-24 probes in field conditions represents one of the most underestimated challenges of multi-probe geophysical surveys. Poor cable management leads to tangling, connection errors, tripping hazards, and wasted time during deployment and recovery. The following systematic approach transforms cable logistics from a frustration into a repeatable, efficient procedure.

6.5.1 The Cable Challenge

A standard 20-probe HIRT deployment involves 20 individual 3-5 meter cables, creating 60-100 meters of total cable length that must be routed, connected, and managed across uneven terrain. In wet or muddy conditions, cables become heavy and prone to picking up debris. Without a systematic approach, deployment can devolve into “cable spaghetti” where identifying connections becomes guesswork and extraction takes twice as long as installation.

The key principle is that **systematic deployment prevents chaotic recovery**. Investing 10 minutes in organized cable routing saves 30 minutes during extraction and dramatically reduces connection errors.

6.5.2 Labeling System

Implement a dual-coded labeling system that provides both visual (color) and alphanumeric (label) identification:

Color Coding by Zone: Divide the probe array into 4-6 zones based on spatial grouping (e.g., North, South, East, West for square grids). Assign each zone a color using colored heat-shrink tubing or tape applied near both cable ends. This allows rapid visual identification from a distance and helps operators route bundles correctly.

Common zone color schemes: - North (blue), South (red), East (green), West (yellow) - Quadrants: Q1 (blue), Q2 (green), Q3 (yellow), Q4 (red) - Sequential zones: Z1 (blue), Z2 (green), Z3 (orange), Z4 (purple)

Numbered Labels: Apply waterproof numbered labels (printed on heat-shrink tubing or laminated paper) at both ends of each cable. Use probe numbering that matches your grid layout (e.g., P01, P02, … P20). Verify that labels remain legible after exposure to mud, rain, and handling.

Field Tip: Label Durability

Print labels on waterproof laser-printable heat-shrink tubing (e.g., 3:1 ratio polyolefin) and apply with a heat gun. This creates permanent, abrasion-resistant labels that survive multiple field deployments. Alternatively, laminate paper labels and secure with clear heat-shrink as an outer layer.

6.5.3 Deployment Sequence

Deploy probes and cables in a systematic order rather than randomly inserting probes wherever convenient. Two effective patterns are:

Spoke Pattern (Radial Deployment): Place the base hub at grid center or edge. Deploy probes moving outward from hub in radial spokes, laying cables as you go. This naturally organizes cables by direction and minimizes crossing.

1. Start with probes nearest the hub
2. Work outward along each cardinal direction (N, S, E, W)
3. Fill in intermediate positions between spokes
4. Each cable follows a direct radial path to hub

Sequential Row/Column Deployment: For rectangular grids, deploy row-by-row or column-by-column. This works well when the hub is positioned along one edge.

1. Deploy entire first row/column with cable bundle
2. Move to next parallel row/column
3. Keep cable bundles parallel and organized by row
4. Hub receives all cables from one side

Regardless of pattern, the key is **consistency**. The same deployment sequence should be followed for extraction, simplifying identification and reducing the chance of leaving equipment behind.

6.5.4 Cable Routing and Management

Slack Management: Keep excess cable coiled at the probe end, not at the hub. This prevents a tangled mass at the central connection point and makes individual probe adjustments easier. Use 2-3 loose coils secured with a single velcro tie at each probe location.

Elevated Routing in Wet Conditions: In muddy or waterlogged sites, elevate cables above ground level using survey stakes or improvised supports. This prevents cables from sinking into mud, reduces debris pickup, and makes extraction far cleaner. Position stakes at 2-3 meter intervals and secure cables with velcro ties or clips.

Avoid Crossing Cables: Design your routing pattern to minimize cable crossings. Where crossings are unavoidable, mark the intersection with a small flag or bright tie so operators know to untangle in reverse order during extraction.

Bundle Parallel Runs: When multiple cables follow the same path (common in spoke patterns), bundle them together with velcro ties every 2 meters. This prevents individual cables from wandering and reduces tangling. Do not use zip ties (difficult to remove for adjustment) or excessive tension (damages insulation).

6.5.5 Connection Protocol

Follow a systematic connection sequence to reduce errors and enable quick troubleshooting:

1. **Dry-fit First**: Before inserting probes, lay out all cables and verify labeling is correct. Match probe numbers to grid positions on paper.
2. **Verify Continuity**: Before burial or full insertion, use a multimeter to quick-check resistance across cable ends (should read low ohms for good connections, open circuit for breaks).
3. **Connect in Order**: Plug cables into the base hub in sequential order (P01, P02, P03…). This makes troubleshooting far easier than random connection order. Mark each port on the hub with corresponding probe numbers.
4. **Quick Resistance Check**: After all connections are made, run a rapid resistance check across all probe pairs. This catches connector issues before beginning lengthy measurement sequences.

Field Tip: Connection Error Prevention

Take a photo of the fully connected base hub showing all cable labels plugged into their ports. If a cable becomes dislodged during the survey, this photo provides instant verification of correct reconnection without consulting field notes.

6.5.6 Teardown and Recovery Procedure

Systematic teardown in reverse order of deployment prevents cable tangling and ensures no equipment is left behind:

1. **Disconnect in Reverse Order**: Unplug cables from hub in reverse sequence (P20, P19, P18...). Coil each cable immediately upon disconnection before moving to the next.
2. **Over-Under Coiling Method**: Use the over-under coiling technique to prevent cable twisting. Alternate hand orientation with each loop: one loop with palm up, next loop with palm down. This creates a flat coil that unrolls without kinking.
3. **Inspect During Coiling**: As each cable is coiled, visually inspect for damage: nicks in insulation, bent connector pins, strained strain relief. Mark damaged cables for immediate repair before next deployment.
4. **Extract Probes Last**: Remove cables first, then extract probes. This prevents accidentally pulling on connected cables during probe extraction, which can damage connectors or pull cables into mud.
5. **Clean Before Storage**: Wipe cables clean with a damp cloth while coiling. Removing mud and debris in the field is far easier than cleaning dried, caked-on soil in the lab.

6.5.7 Storage and Transport

Proper storage prevents connector damage, cable tangling, and corrosion between field sessions:

Individual Cable Bags or Spools: Store each cable in a separate bag (ziplock or mesh) or on a small spool. Label the bag/spool with the cable number. This prevents tangling during transport and makes setup at the next site faster.

Dry Storage: Never store cables while wet or damp. Moisture trapped in connector housings promotes corrosion of pins and sockets. If cables get wet in the field, hang them to dry before coiling for storage.

Connector Protection: Use dust caps on all connectors during storage. For DIY systems, 3D-printed caps or simple plastic bags secured with rubber bands prevent dirt intrusion and pin damage.

Transport Organization: Use a dedicated cable bag, bin, or foam-lined case with compartments. Organize cables by zone (matching field deployment zones) so setup at the next site follows a familiar pattern.

Field Tip: Pre-Deployment Prep

Before leaving for a survey, lay out all cables in deployment order at the lab. This verifies you have the correct number, labels are legible, and connectors are clean. Taking 15 minutes for this check prevents discovering missing or damaged cables after probes are already in the ground.

6.5.8 Quick Reference: Cable Management Checklist

Pre-Deployment: - [ ] All cables labeled with zone color and probe number - [ ] Labels legible and waterproof - [ ] Connectors inspected and clean - [ ] Correct count verified (match number of probes)

Deployment: - [ ] Systematic deployment pattern chosen (spoke or sequential) - [ ] Slack coiled at probe end, not hub - [ ] Cables elevated in wet conditions - [ ] Parallel runs bundled with velcro ties - [ ] Connections verified before measurement

Recovery: - [ ] Disconnect in reverse order - [ ] Over-under coiling method used - [ ] Visual inspection during coiling - [ ] Cables cleaned before storage - [ ] All cables accounted for (count matches deployment)

Storage: - [ ] Individual bags or spools - [ ] Connectors protected with caps - [ ] Dry storage environment - [ ] Organized by zone for next deployment

6.6 Handling Field Obstructions

Real-world field conditions rarely permit idealized grid placement. Tree roots, rocks, standing water, and buried utilities require adaptive deployment strategies. The key principle is that **inversion algorithms use actual sensor positions**—accurate documentation of where probes are matters more than achieving perfect grid geometry.

6.6.1 When to Relocate vs Skip

Table 15: *Decision guidance for probe placement around obstructions*

Situation	Recommended Action	Notes
Small root/rock at surface	Offset probe 10-30 cm	Record actual position
Large obstruction (tree, boulder)	Skip position entirely	Document in survey notes
Standing water/soft ground	Relocate to firm ground	May need wider offset
Buried utility (confirmed)	Skip with 1 m clearance	Safety priority
Partial insertion possible	Insert to achievable depth	Record actual depth

6.6.2 Partial Depth Insertion

When a probe cannot reach full target depth due to subsurface obstructions (rock, dense clay, buried debris), partial insertion remains valuable:

1. **Record the actual tip depth** in survey geometry file (see Section 26.6)
2. **Note the obstruction type** in field log (rock, clay, unknown)
3. **Sensors above the obstruction remain valid** for measurements
4. **Exclude sensors below tip depth** during inversion processing
5. **Consider progressive deployment**: Start shallow (1 m), assess data, then extend depths in clear areas

> **i** Partial Probes Are Still Useful
>
> A probe reaching only 2 m instead of 3 m still provides valid measurements for the upper sensors. The inversion mesh simply excludes electrode positions below the actual tip depth. This is far better than no probe at all.

6.6.3 Position Measurement Procedures

Accurate position recording enables proper inversion geometry. Three levels of precision are available depending on site requirements:

Level 1: Tape Measure (Standard)

For most surveys, tape measure positioning relative to grid origin provides adequate precision:

1. **Establish grid origin** at a marked reference point (survey stake, corner post)
2. **Measure X offset** along the primary baseline direction
3. **Measure Y offset** perpendicular to baseline
4. **Record to nearest 5 cm** (sufficient for ~2 m probe spacing)
5. **Note direction convention** (e.g., X = East, Y = North)

Level 2: Total Station (High Precision)

For surveys requiring cm-level accuracy or complex topography:

1. Set up total station with backsight to known point
2. Record each probe position as Easting, Northing, Elevation
3. Export coordinates to survey geometry file
4. Include surface elevation for topographic correction

Level 3: RTK-GPS (Absolute Coordinates)

For integration with GIS or multi-day surveys:

1. Establish RTK base station or connect to CORS network
2. Record WGS84 coordinates for each probe position
3. Include surface elevation (Z_surface)
4. Transform to local grid if needed for inversion software

6.6.4 Surface Elevation Recording

When ground surface varies across the survey area (slopes, undulating terrain, crater edges), record surface elevation at each probe position:

Table 16: *Surface elevation recording requirements*

Surface Variation	Action Required	Impact on Inversion
< 20 cm across grid	Record as flat (Z=0)	Negligible
20-50 cm variation	Relative elevations	Minor mesh adjustment
> 50 cm variation	Full topographic survey	Required for accuracy

For significant topography, record:

- **z_surface_m**: Ground surface elevation relative to lowest point (or absolute)
- **z_tip_m**: Probe tip depth below local surface (always negative)
- The absolute tip position is then: z_surface_m + z_tip_m

6.6.5 Photograph Documentation

Supplement numerical records with photographs showing:

- Overview of deployed grid with numbered markers visible
- Close-up of any offset or skipped positions with obstruction
- Reference scale in frame (survey stake with depth markings)
- GPS screenshot if using handheld unit

6.7 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.

6.7.1 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.

6.8 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.

6.8.1 Frequency Selection

Table 17: *MIT frequency selection guide for different survey objectives*

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

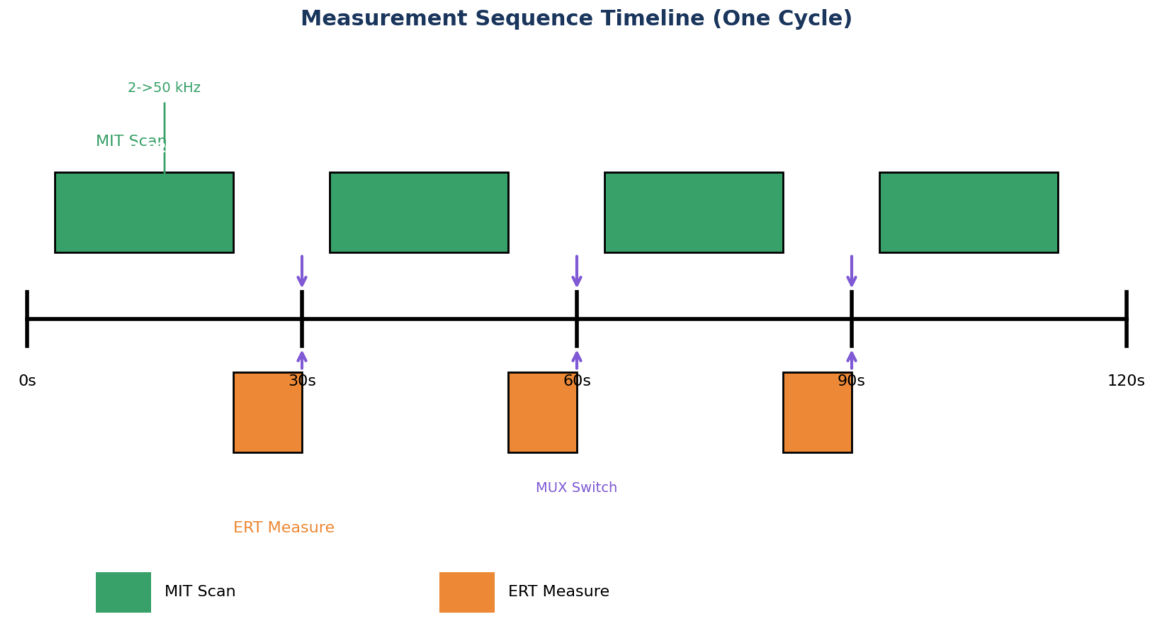

Figure 4: *Measurement sequence timeline showing interleaved MIT scanning and ERT measurement cycles. MIT scans sweep through frequencies (2-50 kHz) while ERT measurements occur during multiplexer switching intervals.*

6.8.2 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

6.9 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.

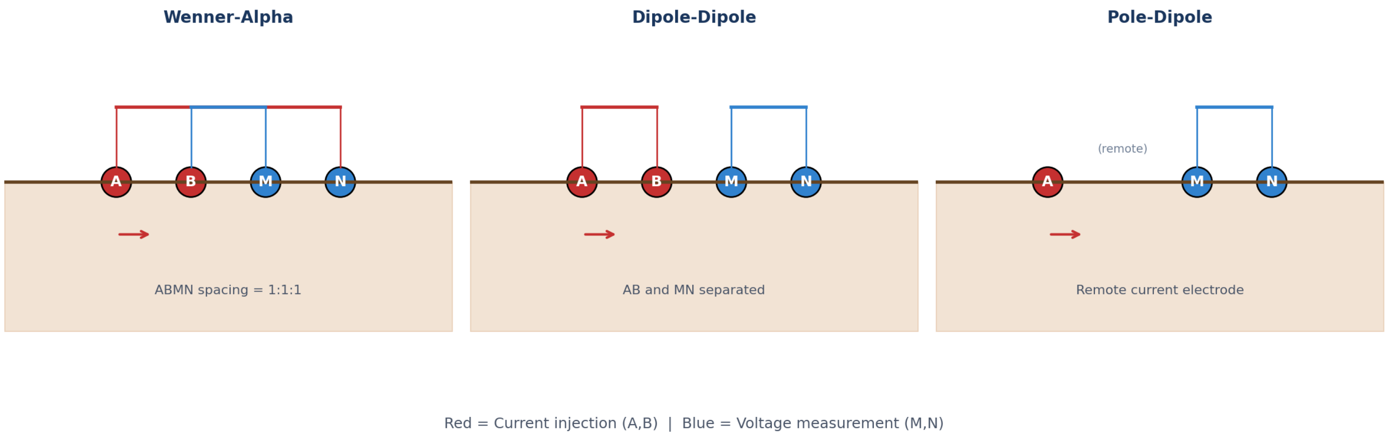

Figure 5: *ERT injection pattern options. (a) Wenner-Alpha: symmetric ABMN spacing for uniform sensitivity. (b) Dipole-Dipole: separated current and voltage dipoles for lateral resolution. (c) Pole-Dipole: remote current electrode for deep penetration.*

6.9.1 ERT Configuration Parameters

Table 18: *ERT measurement 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

6.10 "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.

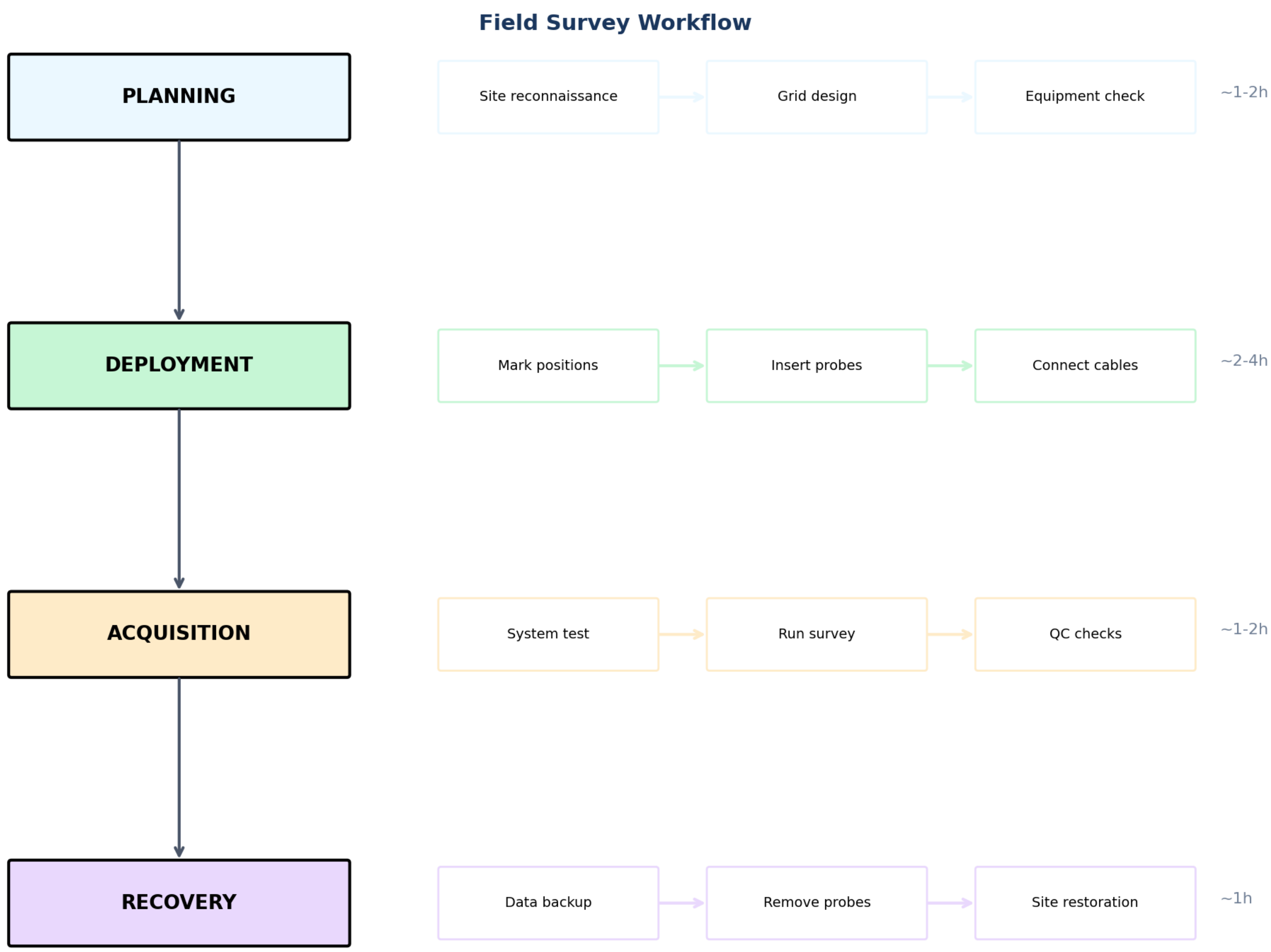

Figure 6: *Complete field survey workflow showing four phases: Planning (site reconnaissance, grid design, equipment check), Deployment (marking, insertion, cabling), Acquisition (system test, survey execution, QC checks), and Recovery (backup, extraction, restoration).*

6.10.1 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.

6.11 Quality Checks

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

6.11.1 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

6.12 Deployment Scenarios

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

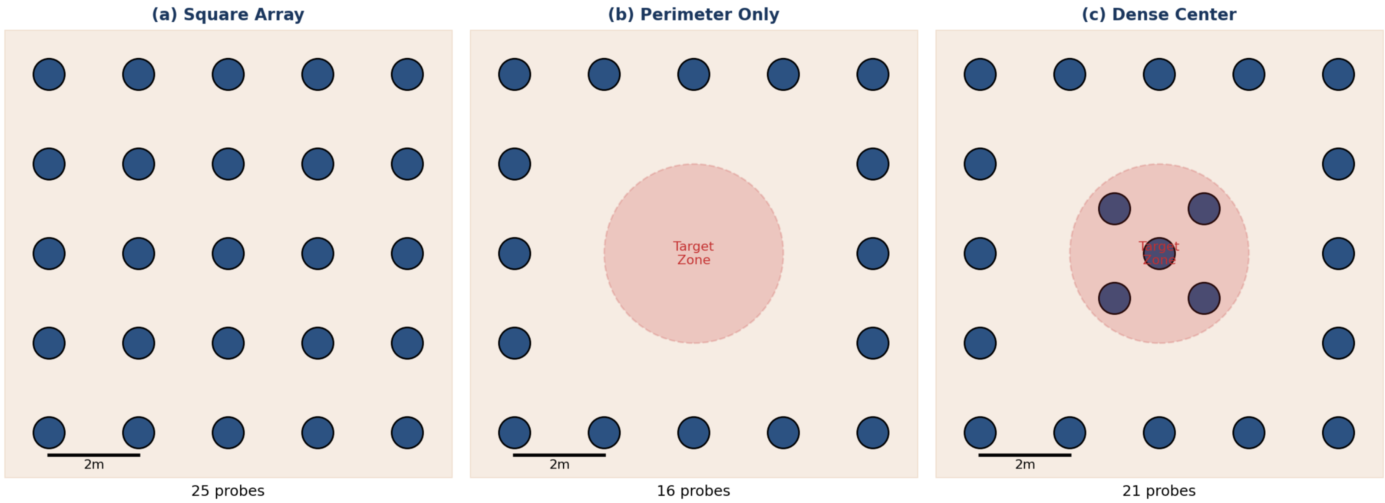

Figure 7: *Deployment scenario configurations. (a) Square Array: uniform coverage for general surveys (25 probes). (b) Perimeter Only: ring deployment around known target zone for minimal disturbance (16 probes). (c) Dense Center: enhanced resolution over target with perimeter context (21 probes).*

6.12.1 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

6.13 Time Estimates

Table 19: *Time estimates for standard 10x10 m section survey*

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

6.14 Shutdown and Data Backup

6.14.1 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.

6.14.2 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

6.14.3 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.

6.15 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

6.16 Equipment Maintenance and Storage

6.16.1 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.

6.16.2 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 29.1. For troubleshooting guidance, see Section 11.1. For calibration procedures, see Section 17.1.

7 Progressive Deployment

7.1 Overview

Progressive deployment is an **advanced workflow** that starts with shallow probe insertion and extends depth incrementally based on data analysis. This approach reduces risk, conserves resources, and enables data-driven decision making about where additional depth is warranted.

When to Use Progressive Deployment

This is an advanced technique for experienced operators. New users should first master **standard fixed-depth deployment** (see Deployment) before attempting progressive workflows.
Best suited for: - Large area reconnaissance where full-depth coverage is impractical - Sites with suspected UXO where minimizing ground disturbance is critical - Challenging soil conditions where depth achievement is uncertain - Research applications requiring depth-resolved data

7.2 Philosophy and Rationale

7.2.1 Why Progressive Approach Works

Traditional geophysical surveys commit to a single deployment depth across the entire grid. This creates inefficiency: some areas may be over-sampled (features are shallow), while others are under-sampled (features are deeper than probes reach).

Progressive deployment addresses this by:

1. **Collecting data before committing resources -** Shallow survey reveals where deeper investigation is needed
2. **Reducing mechanical risk -** Fewer deep insertions means less chance of hitting obstructions

3. **Enabling adaptive sampling** - Focus effort where anomalies indicate potential targets
4. **Preserving site integrity** - Minimize ground disturbance in sensitive areas

7.2.2 Data-Driven Depth Decisions

After each phase, operators analyze data to answer:

- **Where are anomalies detected?** –> Extend depth in those areas
- **Where is background homogeneous?** –> Shallow data may be sufficient
- **What depth do anomalies appear?** –> Plan next extension accordingly
- **Are there indications of deeper features?** –> Continue extension

This transforms deployment from a single large commitment into an iterative refinement process.

7.3 Four-Phase Workflow

```
Phase A          Phase B          Phase C          Phase D
Shallow Survey --> Review Data --> Selective Extend --> Full Depth
   (0.5-1.0m)                     (1.5-2.5m)       (2.5-3.0m)
     |               |                |               |
     v               v                v               v
 Coverage map   Decision tree    Target areas     Complete data
```

7.3.1 Phase A: Shallow Survey (0.5-1.0 m)

Objective: Establish baseline coverage and identify areas of interest.

Procedure:

1. Deploy probes to shallow depth (0.5-1.0 m) across entire grid
2. Acquire MIT and ERT data at all frequencies/patterns
3. Document any insertion difficulties (mark for later attention)
4. Generate preliminary tomograms
5. Export coverage quality metrics

Duration: 60-90 minutes for 4×4 grid (probe insertion faster at shallow depth)

Data Products:

- Shallow depth slice tomograms
- Coverage quality map
- Anomaly detection summary (depth-limited)

Decision Point: After Phase A data review, categorize each grid cell:

Category	Shallow Result	Action
Clear	No anomalies	May be complete (depends on target depth expectations)
Anomaly detected	MIT and/or ERT signal	Extend to Phase C
Ambiguous	Weak or edge signals	Consider extension or adjacent coverage
Insertion problem	Probe didn't reach depth	Attempt different position or water-jet assist

7.3.2 Phase B: Data Assessment

Objective: Review Phase A results to guide selective extension.

Analysis Steps:

1. **Generate depth slices** at 0.25 m intervals through shallow volume
2. **Identify anomalies** using standard classification criteria

3. **Assess background** uniformity and noise levels
4. **Map priority zones** for deeper investigation
5. **Plan extension sequence** (order of probe deepening)

Key Questions:

- Do detected anomalies suggest targets at shallow depth (complete) or indicators of deeper features (extend)?
- Which anomalies have highest investigation priority?
- Are there coverage gaps that need lateral infill before depth extension?
- What is the expected depth range for targets based on site context?

Output: Prioritized list of probes for depth extension, with target depths.

7.3.3 Phase C: Selective Extension (1.5-2.5 m)

Objective: Extend probes to intermediate depth in priority zones only.

Procedure:

1. Leave non-priority probes at shallow depth (they continue to provide data)
2. For each priority probe (in sequence):
   a. Disconnect cable from zone hub
   b. Add rod segment(s) to reach target depth
   c. Advance probe using appropriate method
   d. Reconnect cable, verify connection
3. Acquire new measurement cycle (full array, all depths)
4. Reassess anomalies with improved depth coverage

Critical Technique: In-place extension (see Section 7.4 below)

Duration: 15-30 minutes per probe extended (depends on soil conditions)

Decision Point: After Phase C data:

Result	Action
Target localized at intermediate depth	May be complete; plan excavation
Anomaly continues deeper	Proceed to Phase D (full depth)
Anomaly resolved as natural feature	No further extension needed
New anomalies revealed	Assess for additional extension

7.3.4 Phase D: Full Depth Survey (2.5-3.0 m)

Objective: Achieve maximum depth at selected positions for complete characterization.

Procedure:

1. Extend remaining priority probes to full depth
2. Consider extending adjacent probes for improved deep coverage
3. Acquire final measurement cycle
4. Generate complete depth-resolved tomograms

Final Data Products:

- Multi-depth tomogram stack
- Target localization with depth estimate
- Coverage quality assessment
- Recommendations for excavation

7.4 In-Place Extension Procedure

The modular M12 connector system enables depth extension without removing the probe from the ground.

7.4.1 Equipment Required

- Additional rod segments
- M12 extension cables
- Soft mallet (for final seating only)
- Insertion tool (push handle or hydraulic assist)

7.4.2 Step-by-Step Procedure

Step 1: Prepare Extension

- Disconnect probe cable from zone hub
- Inspect connector for debris or damage
- Have extension segment ready with fresh O-ring

Step 2: Connect New Segment

- Align connector (key-way orientation)
- Hand-tighten M12 connection
- Verify cable routing won't snag during push

Step 3: Advance Probe

- Apply steady downward pressure
- Use push handle or hydraulic assist
- **DO NOT hammer** (UXO safety, connector damage risk)
- Advance until new segment shoulder is at grade

Step 4: Verify and Reconnect

- Check that connector remained secure during push
- Reconnect cable to zone hub
- Run quick check (probe responds to ping)
- Note achieved depth in field log

7.4.3 Connector Contamination Prevention

⚠ Critical: Protect Connectors

The M12 connectors are the most vulnerable component during in-place extension. Soil contamination can cause:

- Electrical contact failure
- Water ingress on later submersion
- Mechanical binding during future disconnection

Prevention measures:

- Cap disconnected connectors immediately
- Keep connection point above ground level during push
- Clean connector faces before each reconnection
- Carry spare O-rings and cleaning supplies

7.4.4 Cable Slack Management

When extending probes in place, the cable must have sufficient slack to accommodate the additional depth without tension on the connector.

Planning for Slack:

Final Depth	Minimum Cable Slack	Recommendation
1.5 m	0.5 m	Standard cable adequate
2.5 m	1.0 m	Coil excess near zone hub
3.0 m	1.5 m	Use extended cables

Slack Management Technique:

1. Before Phase A, deploy with excess cable coiled at surface
2. As probes extend, feed slack into the hole
3. Never allow cable tension during push operation
4. After extension, route cable neatly to zone hub

7.5 Push System Integration

For depths beyond what hand-pushing can achieve, integrate with mechanical push systems.

7.5.1 Strategy A: Two-Pass Method

Concept: Leave sensor probe at shallow depth; use separate push tool for deeper pilot hole.

1. Create pilot hole with hydraulic push system (no sensors)
2. Extract push tool
3. Insert sensor probe into prepared hole
4. Probe slides easily into pre-formed hole

Advantages:

- Sensor probes never subjected to high push force
- Can use expendable pilot rods for difficult soils
- Pilot hole can be slightly oversized for easy insertion

Disadvantages:

- Requires two insertions per position
- Hole may collapse in unstable soils
- Alignment between pilot hole and probe

7.5.2 Strategy B: Direct Push

Concept: Push sensor probe directly with hydraulic assistance.

1. Sensor probe attached to push system head
2. Apply steady hydraulic force
3. Advance probe to target depth in single operation

Advantages:

- Single insertion operation
- No alignment issues
- Works in collapsing soils

Disadvantages:

- Subjects sensors to push force
- Requires robust connector design
- Push force transmitted through probe body

7.5.3 HMIS System Specifications

For sites requiring mechanical push assistance, the HIRT Modular Insertion System (HMIS) provides a purpose-built solution.

Specification	Value
Push force	8-10 kN maximum
Weight	75-100 kg total system
Stroke	1.5 m (single operation)
Power	Battery (48V) or 12V vehicle
Anchoring	4× helical ground anchors
Control	50 m tethered remote
Transport	2-person carry, fits in SUV

Specification	Value

Estimated Cost: $6,200-11,300 complete system

See research documentation: `research/deployment/probe-insertion-methods-summary.md`

7.6 UXO Safety Protocols

Progressive deployment at UXO-suspected sites requires additional safety measures.

7.6.1 Magnetometer Clearance at Each Depth

Before extending to each new depth, verify the look-ahead zone is clear of ferromagnetic anomalies.

Procedure:

1. Use MIT channel in passive mode (TX off) if available
2. Or use separate fluxgate magnetometer probe
3. Clear volume: 1.5-2.0 m below current probe tip
4. Abort threshold: >100 nT anomaly within look-ahead zone

7.6.2 Abort Thresholds by Depth

Depth	Magnetic Threshold	ERT Threshold	Action
0-1.0 m	100 nT	5,500 μS/cm	Caution, may proceed
1.0-2.0 m	50 nT	4,000 μS/cm	Pause, assess
>2.0 m	25 nT	3,000 μS/cm	Stop, consult EOD

7.6.3 Two-Pass Clearance Sequence

For maximum safety at high-risk sites:

1. **Pass 1 (Shallow):** Deploy entire grid to 0.5 m
   - Clear look-ahead before each probe
   - Generate shallow anomaly map
2. **Assessment:** Review map with EOD specialist
   - Identify clear zones for extension
   - Mark exclusion zones around anomalies
3. **Pass 2 (Deep):** Extend only in cleared zones
   - Re-clear look-ahead before each extension
   - Maintain standoff from exclusion zones

7.7 Progressive Depth Profile

The following diagram illustrates how progressive deployment builds depth coverage incrementally:

Figure Concept: Progressive Deployment Depth Profile

Cross-section view showing probe array at four stages:

Panel 1 (Phase A): - All probes at 1.0 m depth (uniform shallow) - Sensitivity zone indicated as ellipses between probes - Annotation: "Full lateral coverage, limited depth"

Panel 2 (Phase C - selective): - Some probes extended to 2.0 m (where anomalies detected) - Other probes remain at 1.0 m - Deeper sensitivity zones at extended positions - Annotation: "Targeted depth where needed"

Panel 3 (Phase D - complete): - Priority probes at 3.0 m - Adjacent probes at 2.0 m - Background probes at 1.0 m - Full depth sensitivity at target - Annotation: "Maximum depth at target, efficient coverage elsewhere"

Panel 4 (Comparison with fixed-depth): - All probes at 3.0 m (traditional approach) - Annotation: "Standard approach: same effort everywhere" - Arrow comparing total insertion work

Show surface, probes as vertical lines with electrode rings, target location, ground layers.

Type: cross-section

7.8 When Progressive Deployment Is NOT Appropriate

Progressive deployment adds complexity. Consider fixed-depth deployment when:

- **Survey area is small** (4×4 or smaller) - overhead doesn't justify savings
- **Target depth is known** - no benefit from shallow reconnaissance
- **Time is limited** - multiple passes take longer than single deep deployment
- **Soil is easy** - if full depth is achievable quickly, just do it
- **Reporting requires uniform coverage** - some protocols mandate consistent depth

7.9 Summary: Progressive Deployment Decision Tree

```
START: Survey Planning
          |
          v
    Large area (>25 probes)?
     +-- No --> Standard fixed-depth deployment
     |
     Yes
     |
     v
    Depth uncertainty?
     +-- No --> Standard fixed-depth deployment
     |
     Yes
     |
     v
    UXO concerns?
     +-- Yes --> Progressive with clearance protocol
     |
     No
     |
     v
    Soil variability?
     +-- Yes --> Progressive recommended
     |
     No
     |
     v
    Consider based on cost/benefit
```

7.10 Best Practices

1. **Plan cable slack before deployment** - It's much harder to add later
2. **Protect connectors religiously** - One contaminated connector can ruin a survey
3. **Document actual depths** - Phase B decisions depend on accurate records
4. **Don't skip Phase B** - The data review is what makes progressive deployment worthwhile
5. **Have backup push capability** - If hand-push fails, you need options
6. **Train on easy sites first** - Master the technique before high-stakes deployments

7.11 Related Documentation

- Deployment - Standard fixed-depth procedures
- Safety - UXO safety protocols
- Troubleshooting - Insertion problem solving

- Research: Probe Insertion Methods - Full research summary

8 Data Acquisition

8.1 Overview

This section covers practical data acquisition procedures for HIRT field measurements. For detailed data format specifications and software compatibility, see the Data Formats section in the Developer Guide.

8.2 The Measurement Matrix Concept

HIRT data acquisition is based on a **transmit-receive (TX-RX) matrix**. For an array of N probes:

- Each probe takes turns acting as the **transmitter** (TX)
- While transmitting, **all other probes** simultaneously act as receivers (RX)
- This produces N × (N-1) unique TX-RX measurements per frequency (MIT) or injection pattern (ERT)

For a typical 16-probe array, this yields 240 unique measurements per acquisition cycle—each sampling a different geometric path through the subsurface.

8.3 Probe Coordinate System

Each probe is positioned in 3D space and contains sensors at multiple depths:

Table 25: *Probe coordinate system*

Coordinate	Description	Typical Values
X	Horizontal position (grid column)	0 to 10 m
Y	Horizontal position (grid row)	0 to 10 m
Z	Vertical depth below surface	0 to -3 m (negative = below ground)

Within each probe, multiple sensor rings are spaced along the shaft (e.g., at 0.5 m intervals). A 3 m probe with 0.5 m ring spacing contains **6 electrode rings**, each at a known depth. The complete array therefore samples a 3D volume defined by the probe positions (X, Y) and sensor depths (Z).

8.4 Sequential Acquisition Process

The HIRT controller automates the measurement sequence, cycling through all TX-RX combinations. For MIT measurements, the cycle repeats at each measurement frequency. For ERT, different injection patterns are used.

Typical acquisition sequence:

1. **Select TX probe** and configure transmitter
2. **Activate TX** at specified frequency (MIT) or current (ERT)
3. **Sample all RX probes** simultaneously
4. **Record measurements** to data file
5. **Advance to next TX** and repeat

For a 16-probe array at 5 frequencies, this produces approximately 1,200 MIT measurements per acquisition cycle.

8.5 Building 3D Sensitivity Coverage

Each TX-RX measurement samples a specific region of the subsurface. The **sensitivity volume** for a measurement is the region where changes in conductivity/resistivity would affect the measured signal.

The overlapping sensitivity regions from all TX-RX combinations build complete volumetric coverage. This is the foundation of tomographic reconstruction.

8.6 How a Buried Object Appears in the Data

When a conductive object (such as buried metal) is present in the subsurface, it perturbs the electromagnetic field between TX-RX probe pairs. The strength of this perturbation depends on whether the object lies within the sensitivity region of each measurement. By examining which TX-RX pairs show anomalous readings, the inversion algorithm localizes the object in 3D space.

The pattern of "high" and "low" responses in the measurement matrix reveals:

1. **Which TX-RX pairs detected the anomaly** (elevated responses)
2. **The approximate target location** (intersection of sensitivity ellipses)
3. **Target characteristics** (metal shows MIT response, disturbed fill shows ERT response)

8.7 Recording Workflow

The HIRT data recording workflow follows a systematic process from site preparation through data backup:

1. **Site preparation** - Grid layout, obstacle assessment
2. **Probe deployment** - Insert probes to target depth
3. **System initialization** - Power-up, cable connections, self-test
4. **Record metadata** - Site info, probe positions, conditions
5. **Start logging** - Begin automated measurement cycle
6. **Measurement loop** - MIT and ERT for each probe pair
7. **Quality check** - Reciprocity validation, noise assessment
8. **Field notes** - Document conditions and observations
9. **Export data** - CSV files and paper log backup
10. **Backup storage** - Multiple copies before leaving site

8.8 Survey Geometry Documentation

The survey geometry file links probe identifiers to their actual field positions, enabling accurate tomographic reconstruction even when probes deviate from ideal grid locations.

Filename convention: `survey_geometry_{YYYY-MM-DD}.csv`

Table 26: *Survey geometry file fields*

Field	Description	Units
probe_id	Probe identifier (matches registry)	String
x_m	X position from grid origin	meters
y_m	Y position from grid origin	meters
z_surface_m	Ground surface elevation (relative)	meters
z_tip_m	Probe tip depth below surface	meters (negative)
status	Deployment status	ACTIVE / PARTIAL / SKIPPED
notes	Field observations	Free text

8.8.1 Status Codes

Table 27: *Probe status codes and their interpretation*

Status	Meaning	Inversion Handling
ACTIVE	Full insertion achieved	All sensors included
PARTIAL	Reduced depth due to obstruction	Exclude sensors below z_tip
SKIPPED	Position not deployed	Omit from geometry

Recording Best Practice

Complete the survey geometry file **before** leaving the field site. Position measurements are difficult to reconstruct after extraction. Take photographs of the deployed array with visible probe markers as backup documentation.

8.9 Coordinate System Convention

For consistency across surveys, adopt a standard local coordinate system:

- **Origin (0, 0, 0):** First probe position or marked survey stake
- **X-axis:** Primary baseline direction (typically longest dimension)
- **Y-axis:** Perpendicular to X, following right-hand rule
- **Z-axis:** Positive upward; surface elevations positive, tip depths negative
- **Units:** Always meters with two decimal places

When using GPS or total station, record the transformation parameters (origin coordinates, rotation angle) to enable conversion between local and absolute coordinates.

8.10 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.

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

8.11 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

9 Data Interpretation

9.1 Overview

This section provides practical guidance on interpreting HIRT field data, including what each measurement method detects, how to classify anomalies, and how to prioritize investigation targets. For the mathematical foundations and inversion algorithms, see Theory: Inversion.

Effective interpretation requires understanding both the physics of the measurements and the geological/archaeological context of the survey site.

9.2 What HIRT Detects

9.2.1 MIT (Magneto-Inductive Tomography) Detection

The MIT-3D channel responds to materials with electrical conductivity and/or magnetic permeability:

- **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

9.2.2 ERT (Electrical Resistivity) Detection

The ERT-Lite channel responds to variations in bulk electrical resistivity:

- **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

9.3 Anomaly Classification

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

Table 28: *Anomaly classification by target type*

Target Type	MIT Response	ERT Response	Examples
Metal Objects	Strong	Weak/None	Engine parts, wreckage, artifacts
Conductive Soil	Moderate	Moderate	Wet clay, saline zones, contamination
Disturbed Fill	Weak	Strong	Crater fill, grave shafts, backfill
Voids/Air	None	Strong (high-R)	Cavities, collapsed zones, air pockets
Moisture Zones	Weak	Strong (low-R)	Water table, wet pockets, seepage

Key insight: Combine MIT + ERT for complete picture. A metallic target in disturbed fill shows both strong MIT response AND ERT contrast—this is a high-priority combination.

9.4 Combined Interpretation Strategy

Effective HIRT interpretation combines MIT and ERT results with site context and historical information.

9.4.1 Decision Tree for Prioritization

1. **Verify data quality** - Check reciprocity, noise levels
2. **Identify MIT anomalies** - Strong, moderate, or absent?
3. **Identify ERT anomalies** - Resistivity higher or lower than background?
4. **Correlate locations** - Do MIT and ERT anomalies coincide?
5. **Classify target** - Metal, fill, void, or natural feature?
6. **Assign priority** - Based on combined evidence and site context

9.4.2 Priority Levels

Table 29: *Investigation priority levels*

Priority	Criteria	Action
HIGH	Metal + Disturbed fill (both channels)	Immediate investigation
MEDIUM	Metal OR fill only (one channel)	Further characterization
LOW	Minor anomalies, weak signals	Document for reference
NATURAL	ERT-only, no MIT, natural geometry	Likely root mass, clay lens

9.5 Example Interpretation Scenarios

9.5.1 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

9.5.2 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

9.5.3 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

9.6 Target Signature Catalogue

9.6.1 Metallic Object Signatures (MIT-3D)

Ferrous Metal (Iron/Steel): Aircraft engines, landing gear, bomb casings, and steel artifacts produce the strongest MIT responses. The combination of high electrical conductivity and magnetic permeability creates intense eddy currents and magnetic field distortion.

Non-Ferrous Metal (Aluminum, Brass, Copper): Aircraft structural components, ammunition casings, and decorative artifacts produce moderate MIT responses. These materials lack magnetic permeability but still support eddy currents.

Size vs Depth Relationship: Target detectability follows an approximate cube-law. A 10 cm artifact detectable at 1 m depth becomes nearly invisible at 2 m depth. For planning, assume minimum detectable size scales linearly with depth.

9.6.2 Soil Disturbance Signatures (ERT-Lite)

Backfilled Excavation: Bomb craters, trenches, and excavations refilled with soil show characteristic resistivity patterns. The backfill is typically less compacted, creating larger pore spaces that retain more moisture. This produces a low-resistivity anomaly.

Void/Cavity: Air-filled spaces produce high-resistivity anomalies. Air has effectively infinite resistivity, so even a small void creates a distinct signature.

Decomposition Products: Organic decomposition releases conductive fluids that reduce resistivity. Burial sites often show a moderate low-resistivity zone with elongated geometry.

9.6.3 Combined Signatures (Dual-Channel Fusion)

Bomb Crater with Metallic Debris: Clear bowl-shaped ERT disturbance with strong MIT responses concentrated near the crater base or scattered throughout the fill. Excavation priority is HIGH.

Burial with Metal Artifacts: Modest rectangular ERT disturbance (grave shaft geometry) with small, discrete MIT anomalies aligned with the shaft. The presence of metal increases identification confidence.

Natural Features Mimicking Targets: Tree root masses, clay lenses, and natural soil heterogeneity can produce ERT anomalies. The key discriminator is the MIT channel: natural features almost never produce metal responses.

9.7 False Positives to Watch For

Table 30: *Common false positive sources*

False Positive	Distinguishing Features
Utility pipes	Linear geometry, often straight lines
Natural mineralization	Diffuse, regional trends (not localized)
Root masses	Branching/networked pattern in ERT, no MIT response
Perched water table	Laterally extensive, consistent depth across survey

9.8 Data Quality Indicators

9.8.1 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

9.9 Detection Limits

Understanding what HIRT *cannot* detect is as important as understanding what it can detect.

9.9.1 Typical Anomaly Sizes

Table 31: *Typical anomaly sizes and expected responses*

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

9.9.2 Minimum Detectable Sizes

- **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)

! What "No Anomaly" Actually Means

A survey showing no anomalies indicates "no statistically significant deviation from background within detection limits"—NOT "definitely clear of targets." Small objects, deep targets, or low-contrast features may be present but undetectable.

9.10 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

i 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

10 Application Scenarios

10.1 Overview

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 swamp/marsh crash sites. 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.

10.2 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.

10.2.1 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

10.2.2 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

10.2.3 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

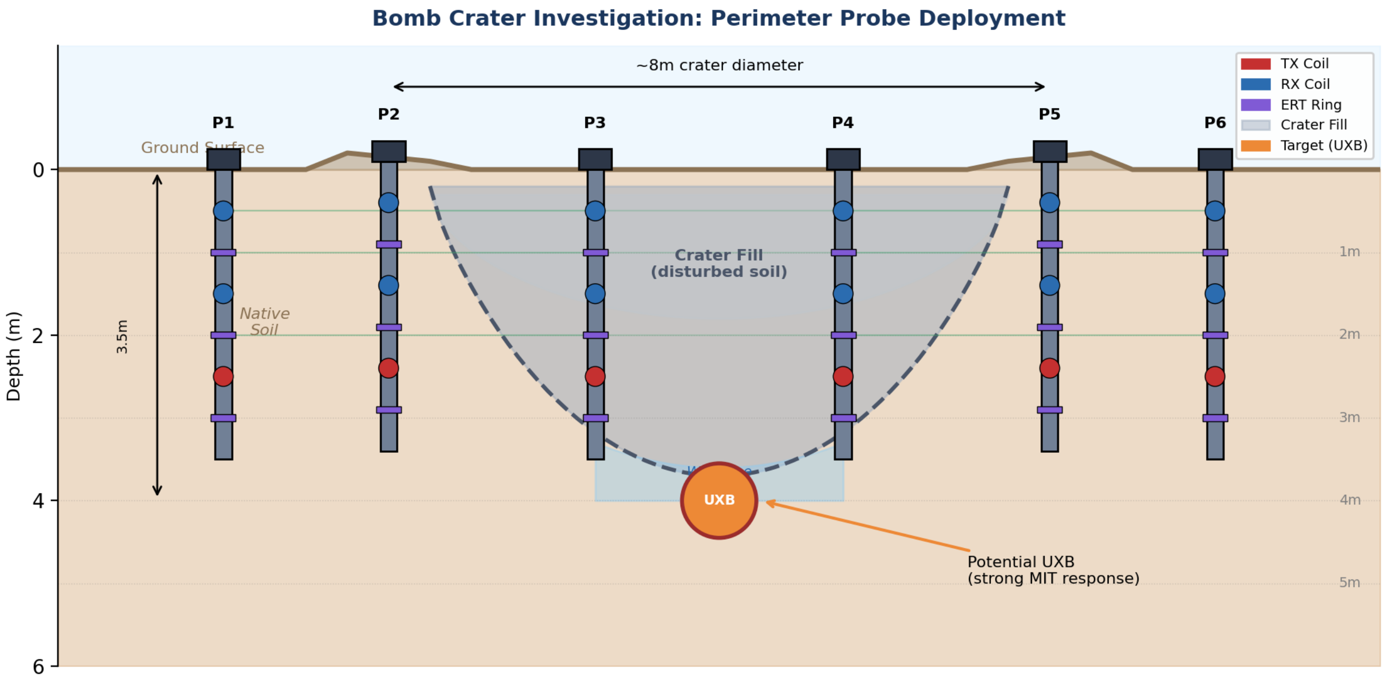

Figure 8: *Bomb crater investigation configuration showing perimeter probe deployment around crater margin. Six 3.5m probes at 2m spacing provide comprehensive coverage through crater fill. MIT ray paths (green) interrogate the full volume including potential UXB location at crater base. ERT rings map fill boundaries and wet zones.*

10.2.4 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.

10.3 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.

10.3.1 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

10.3.2 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

10.3.3 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

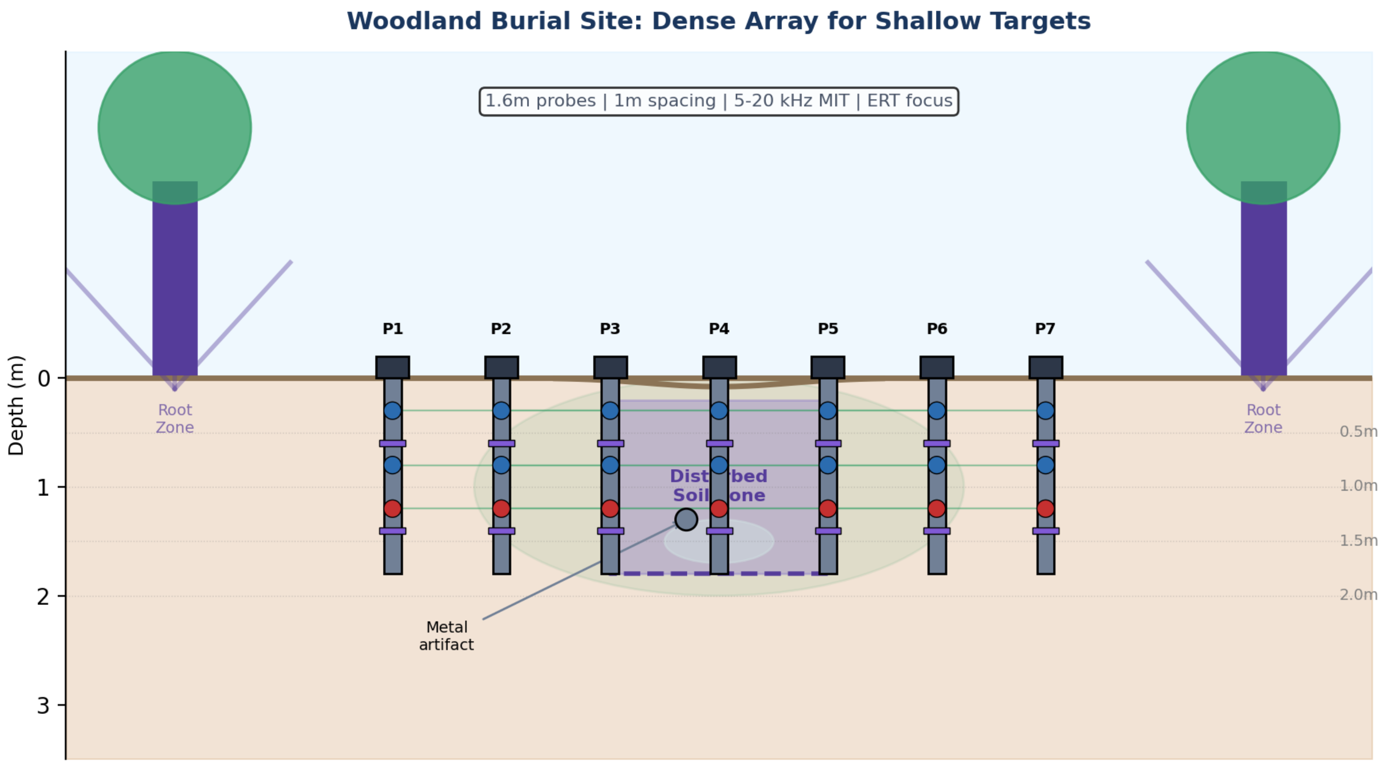

Figure 9: *Woodland burial site configuration showing dense probe array (7 probes, 1m spacing) for shallow target detection. Disturbed soil zone (grave shaft) shows distinct ERT contrast. Tree root systems require careful probe positioning. MIT detects small metallic artifacts (buckles, buttons) within burial context.*

- **Dense Measurement Pattern:** Short baselines for maximum near-surface resolution
- **Complementary Methods:** Coordinate with GPR surface survey if available

10.4 Scenario 3: Swamp/Marsh Crash Sites

Waterlogged and marshy terrain presents unique challenges for aircraft crash investigation. When bombers went down in soft, saturated ground, the combination of impact forces and unstable soil caused aircraft—and their crews—to sink progressively deeper over time. Unlike dry-ground crashes where wreckage remains near the surface, marsh impacts can result in debris fields extending 5-10+ meters below the current surface level.

The soft, organic-rich soil essentially "swallows" the wreckage: initial impact creates a crater that fills with water and sediment, while the weight of aircraft components causes continued subsidence over decades. This phenomenon is well-documented at WWII crash sites in Poland's Silesian marshlands, the Netherlands' polders, and similar low-lying areas across Europe.

10.4.1 The Deep Burial Problem

When aircraft crashed into saturated marshland, several factors combined to drive wreckage deep underground:

1. **Impact penetration:** High-speed impact into soft ground creates an initial crater
2. **Waterlogging:** The crater immediately fills with groundwater
3. **Progressive subsidence:** Heavy metal components continue sinking through soft peat and clay
4. **Sediment accumulation:** Organic material and sediment fill the depression from above
5. **Decades of compression:** 80+ years of soil compaction further buries the debris

The result: aircraft that hit dry ground remain within 1-2 meters of the surface, while marsh impacts can place wreckage 5-10+ meters deep.

10.4.2 Configuration Parameters

- **Rod Length:** Maximum available (3.0-3.5 m) - depth is the primary challenge
- **Probe Spacing:** 2-3 m around the perimeter of the suspected impact zone

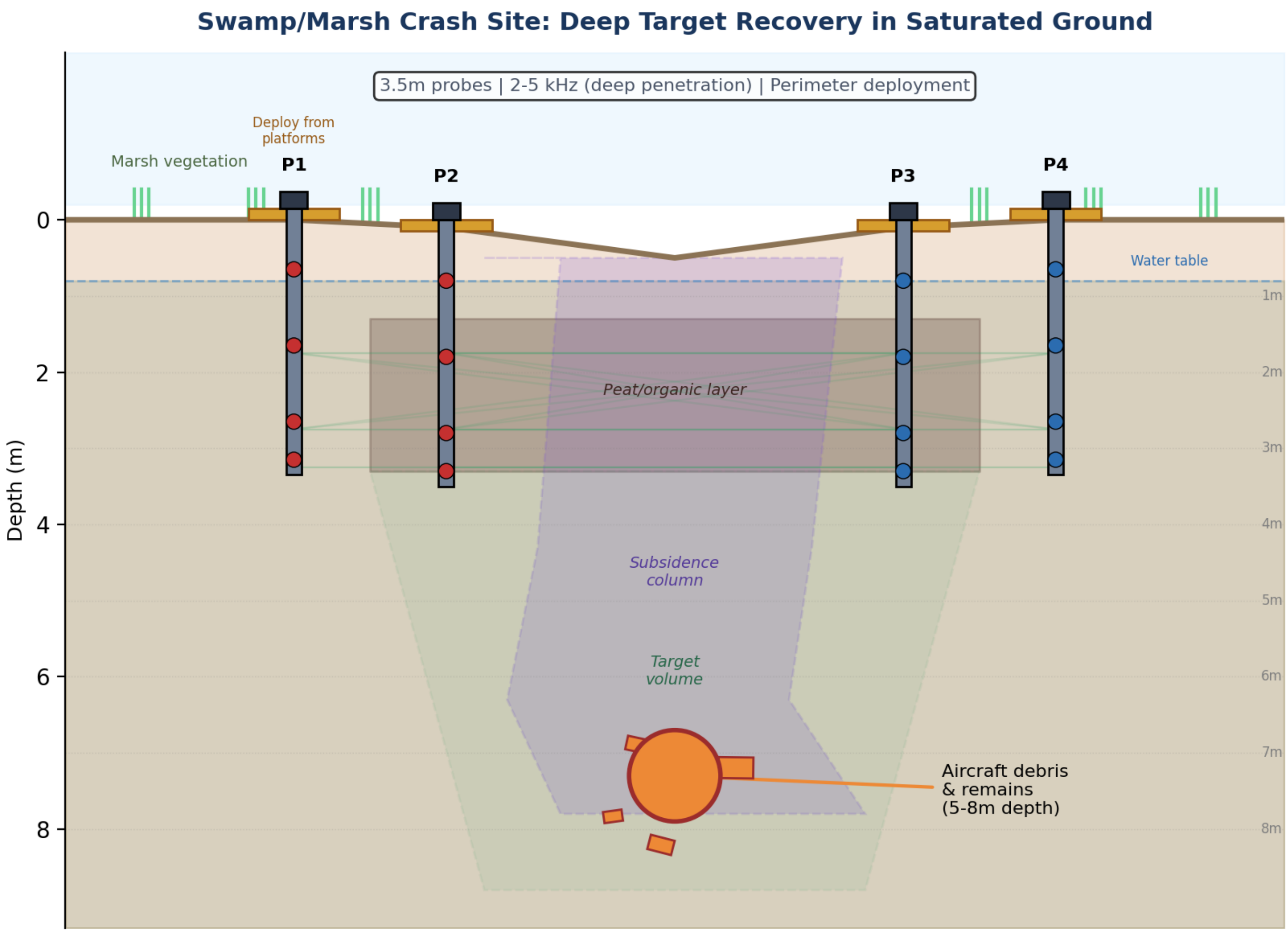

Figure 10: *Swamp/marsh crash site configuration showing probe deployment around the impact zone. Soft, saturated soil caused the aircraft to sink progressively deeper over decades. Extended 3.5m probes with low-frequency MIT (2-5 kHz) are essential for detecting debris at 5-8+ meter depths. Deployment platforms may be required due to soft ground conditions.*

- **Section Size:** 8-12 m diameter coverage for typical bomber crash footprint
- **Probe Count:** 8-12 probes in perimeter configuration
- **Deployment:** Use platforms/boards on soft ground; may require temporary walkways

10.4.3 Measurement Strategy

- **Low MIT Frequencies:** 2-5 kHz essential for maximum depth penetration
- **Extended Integration:** 15-30 second measurements for weak deep signals
- **Multi-Frequency Sweep:** Start at 2 kHz, sweep to 10 kHz to characterize depth
- **ERT for Context:** Maps saturated zones and disturbed fill boundaries
- **Repeat Measurements:** Multiple passes to confirm weak signals at detection limits

10.4.4 Deployment Considerations

Soft ground conditions require careful planning for both safety and data quality:

- **Ground Assessment:** Test soil firmness before committing to probe positions
- **Deployment Platforms:** Plywood boards or temporary walkways distribute weight
- **Probe Insertion:** May require pilot holes; avoid forcing probes through root mats
- **Water Table Effects:** High conductivity of saturated soil limits ERT depth; rely primarily on MIT
- **Seasonal Timing:** Drier seasons may improve access but water table remains high
- **Extended Survey Time:** Budget 2-3x longer than dry-ground surveys

⚠ Detection Limits

Targets at 6+ meters in conductive saturated soil approach HIRT's detection limits. Expect:

- Signal levels 10-20 dB below typical dry-ground responses
- Higher uncertainty in depth estimates
- Possible false negatives for smaller debris fragments
- Need for multiple survey passes to confirm anomalies

Consider complementary methods (seismic, coring) for confirmation of deep targets.

10.5 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.

Table 32: *Summary of configuration parameters by application scenario*

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/Marsh Crash	3.0-3.5 m	2-3 m	2-5 kHz	5-8+ m	Low-freq MIT

10.6 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.

10.6.1 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

10.7 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.

10.7.1 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

10.8 General Field Procedures

10.8.1 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

10.8.2 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

10.8.3 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

10.9 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.

Table 33: *Estimated costs for HIRT system configurations. Actual costs vary by supplier, quantity discounts, and component choices.*

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**

10.9.1 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

10.10 Recommendations

10.10.1 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.

10.10.2 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.

10.10.3 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.

10.11 Case Studies and Field Validation

Empirical validation from prototype deployments provides essential ground truth for HIRT performance claims. This section documents field trials and their outcomes to guide expectations for operational surveys.

> **ℹ Case Study Status**
>
> The case studies below document planned or in-progress field validation efforts. As HIRT prototype testing continues, this section will be updated with actual measurement results, detection outcomes, and lessons learned. Readers should distinguish between **planned** trials (targets identified, testing pending), **completed** trials (measurements taken, results reported), and **validated** outcomes (excavation confirmed interpretation).

10.11.1 Planned Case Study Framework

Each case study follows a standardized documentation format to enable meaningful comparison across sites and configurations:

Site Context:

- Location (generalized to protect sensitive sites)
- Historical background and expected targets
- Soil type and conditions
- Access constraints

Survey Configuration:

- Probe count, spacing, and depth
- MIT frequencies employed
- ERT configuration
- Total measurement time

Results Summary:

- Anomalies detected (number, depth, confidence)
- Excavation outcomes (if performed)
- Detection successes and failures
- Lessons learned

10.11.2 Case Study 1: Controlled Test Site (Validation Pending)

Purpose: Establish baseline detection performance using known buried targets.

Site: University research field with buried test objects at documented depths.

Targets:

- 50 cm steel cylinder at 1.5 m depth
- 30 cm aluminum plate at 1.0 m depth
- 2 m $\times$ 1 m disturbed fill zone (no metal) at 1.5 m depth
- Control area with no buried objects

Configuration:

- 4$\times$4 probe grid, 1.5 m spacing
- 1.8 m probe depth
- MIT frequencies: 2, 5, 10, 20 kHz
- ERT ring positions: 0.5 m, 1.0 m, 1.5 m

Status: Planned. Results will establish SNR baselines, resolution limits, and detection probability for known targets.

10.11.3 Case Study 2: Historical Crash Site Investigation (Validation Pending)

Purpose: Assess HIRT performance in operationally representative conditions.

Site: WWII aircraft crash site with documented historical records but unexcavated debris field.

Expected Targets:

- Engine components (estimated 3-4 m depth based on crater fill)
- Scattered debris field within crater boundary
- Possible human remains in association with wreckage

Configuration:

- Perimeter deployment around crater margin
- 20 probes at 2 m spacing
- 3.0 m probe depth
- Low-frequency emphasis (2-5 kHz) for depth penetration

Status: Awaiting site access approval. Results will validate deep detection claims and inform recovery operations.

10.11.4 Case Study 3: Forensic Search Exercise (Validation Pending)

Purpose: Test woodland burial detection in controlled forensic context.

Site: Law enforcement training facility with documented simulated burial sites.

Targets:

- Simulated grave shafts at 1-2 m depth
- Associated metal artifacts (buttons, buckles) placed with simulated remains
- Control areas with undisturbed native soil

Configuration:

- Dense array (1 m spacing) over search area
- 1.6 m probe depth
- MIT frequencies: 5, 10, 20 kHz
- ERT focus for disturbed soil detection

Status: Coordination with training facility in progress. Results will validate forensic application claims.

10.11.5 Reporting Case Study Results

When case studies are completed, results will be reported with the following metrics:

Detection Performance:

- True positive rate (targets correctly identified)
- False positive rate (anomalies without corresponding targets)
- Detection depth limit (deepest confirmed target)
- Minimum detectable target size at each depth

Interpretation Accuracy:

- Depth estimation error (predicted vs. actual)
- Lateral position error (predicted vs. actual)
- Confidence calibration (did HIGH confidence predictions confirm?)

Operational Metrics:

- Setup time per probe
- Total survey duration
- Data processing time
- Equipment reliability issues

> Contributing Case Studies
>
> HIRT users who conduct field trials with documented ground truth are encouraged to share results for inclusion in this section. Contact information for case study submission will be provided when the HIRT firmware repository is established. Anonymized site data and standardized reporting ensure useful cross-site comparison while protecting sensitive locations.

> 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

11 Troubleshooting

11.1 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.

11.2 Diagnostic Approach

11.2.1 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.

11.2.2 Quick Reference Table

Table 34: *Common symptoms, causes, and solutions*

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

11.2.3 Diagnostic Decision Tree

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

11.3 MIT Troubleshooting

11.3.1 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

11.3.2 Noisy MIT Data

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

Causes: Poor cable shielding, ground loops (multiple ground paths), electromagnetic interference 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 for interference sources:** Move away from power lines, vehicles, radios
6. **Verify connections:** Check all connectors are tight and clean

11.3.3 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

11.4 ERT Troubleshooting

11.4.1 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

11.4.2 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

11.4.3 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

11.5 Power Issues

11.5.1 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

11.5.2 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

11.6 Communication Issues

11.6.1 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 interference sources nearby
6. Restart probe and base hub

11.6.2 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

11.7 Environmental Factors

11.7.1 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

11.7.2 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

11.8 Field Repairs

11.8.1 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

11.8.2 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.

11.8.3 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)

11.9 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

11.9.1 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

11.9.2 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

11.10 Prevention

11.10.1 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

11.10.2 During Survey

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

11.10.3 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**

Part III
Build Guide

12 Bill of Materials

12.1 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.

Hardware Documentation Reference

Detailed, up-to-date BOMs with specific part numbers are maintained in the hardware documentation:

- **Probe BOM:** `/hardware/bom/probe-bom.md` - Per-probe components, costs, and procurement tips
- **Base Hub BOM:** `/hardware/bom/base-hub-bom.md` - Central electronics components with detailed specifications
- **Shared Components:** `/hardware/bom/shared-components-bom.md` - Common components used across multiple assemblies
- **Procurement Guide:** `/hardware/bom/PROCUREMENT.md` - Supplier recommendations and ordering strategies

The tables in this section summarize the BOMs; refer to the hardware documentation for exact part numbers and current pricing.

12.2 Cost Summary

12.3 System Cost Estimate (20-Probe Array)

The following table presents the estimated cost ranges for a complete 20-probe HIRT system based on 2026 manufacturing projections.

Table 35: *20-Probe HIRT System Cost Estimate (2026 Projection)*

Category	Cost Range	Notes
Probes (20 units)	\$840-1,100	CNC Delrin/Nylon mechanics
Electronics (Hubs)	\$450-600	3x Hubs (active architecture)
Cabling	\$300-400	Trunk + Extensions
Assembly Labor	\$600-800	In-house @ \$30/hr
Contingency	\$300-400	Buffer for price hikes
Total	**\$2,150-2,850**	**~\$125 per probe**

⚠ 2026 Supply Chain Alert: Semiconductor Price Hike

Critical: Analog Devices (ADI) has announced a **10-30% price increase** effective February 1, 2026. This affects key components including the AD8421, AD9837, and AD7124. Builders are strongly advised to procure these silicon components immediately to lock in current pricing.

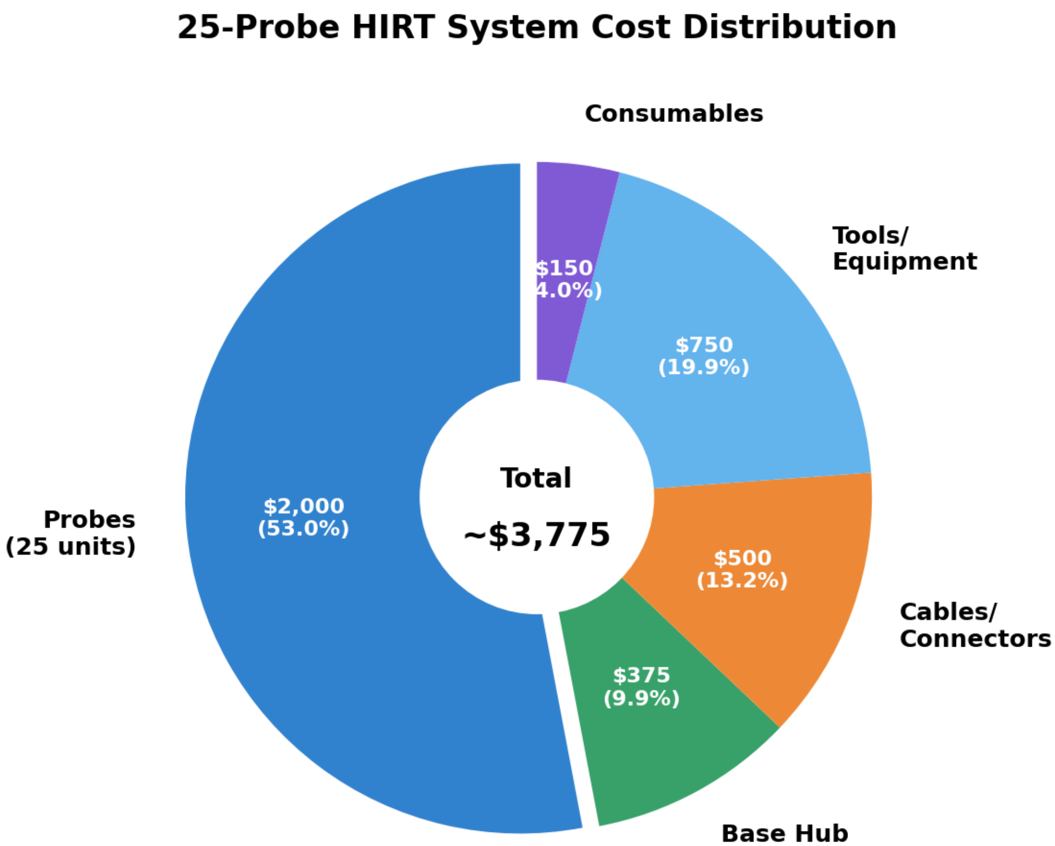

Figure 11: *Cost distribution for a 25-probe HIRT system showing the relative investment in each component category. Probes represent the largest expense due to quantity.*

12.4 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.

Table 36: *Per-Probe Cost Breakdown (Passive Design)*

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**

12.5 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

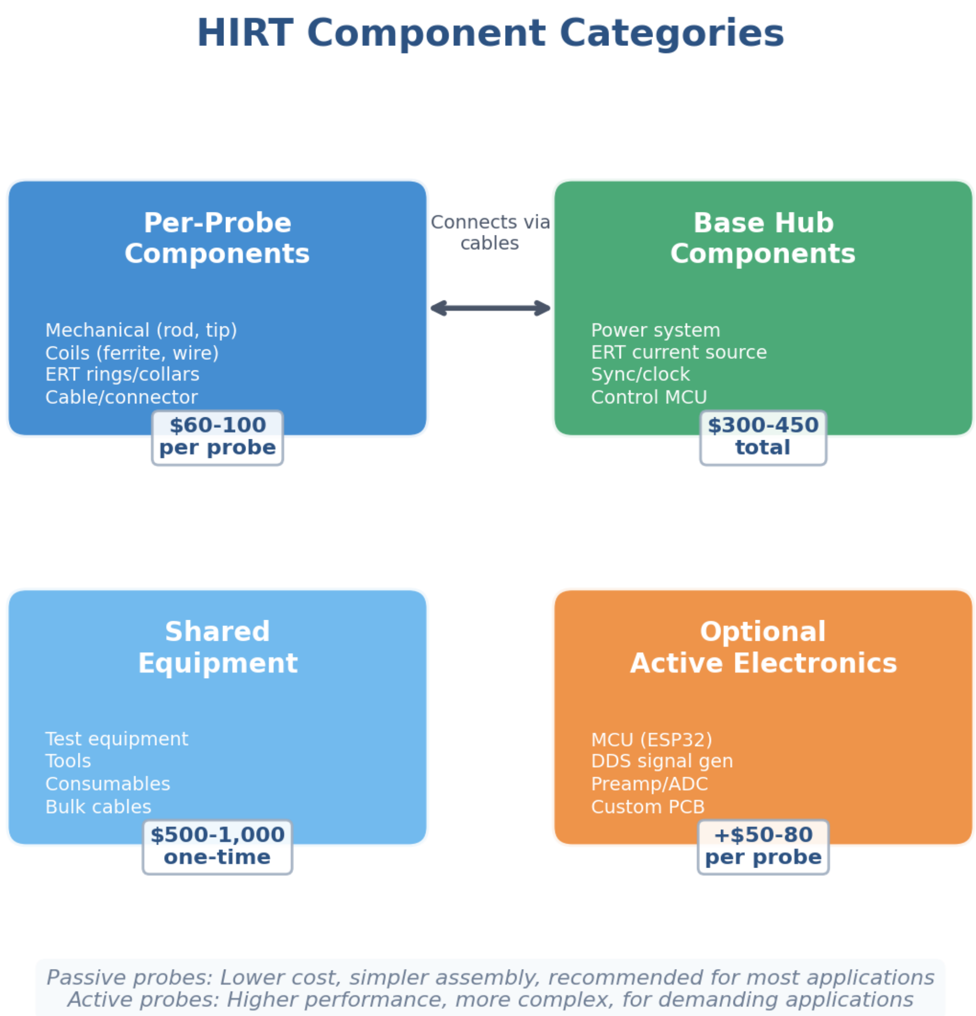

Figure 12: *HIRT component categories showing the relationship between per-probe components, base hub electronics, shared equipment, and optional active probe upgrades.*

12.6 Per-Probe Bill of Materials

12.7 Mechanical Components

Table 37: *Per-Probe Mechanical Components (CNC/Volume Estimates)*

Ref	Component	Description	Qty	Unit Cost (100 qty)
ROD1	Fiberglass Tube	16mm OD x 12mm ID x 1.5m	1.5	$10.00
TIP1	Probe Tip	CNC Delrin (Acetal)	1	$3.80-5.50
CPL1	Rod Coupler	CNC Nylon 6/6	1	$4.20-6.00
JB1	Junction Box	3D printed PETG / CNC	1	$3-5

12.8 Coil Components

Table 38: *Per-Probe 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

12.9 ERT Components

Table 39: *Per-Probe 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

12.10 Hardware

Table 40: *Per-Probe Hardware*

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

12.11 Cable and Connectors

Table 41: *Per-Probe 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

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

12.12 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.

Table 42: *Active Probe Electronics (Optional Add-on)*

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

Ref	Component	Part Number	Qty	Unit Cost
U7	Mux	CD4051BE	1	$1-2
U8	LDO	AMS1117-3.3	1	$0.50
PCB	Custom PCB	-	1	$5-10
-	Passives	Resistors, caps	-	$5

ℹ Note

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

12.13 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.

12.14 Power System

Table 43: *Base Hub Power System Components*

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

12.15 ERT Current Source

Table 44: *ERT Current Source Components*

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

12.16 Sync/Clock Distribution

Table 45: *Sync/Clock Distribution Components*

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

12.17 Communication

Table 46: *Communication Interface Components*

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

12.18 Control

Table 47: *Control System Components*

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

12.19 Enclosure and Connectors

Table 48: *Enclosure and Connector Components*

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

Total Base Hub Cost (2026 Estimate)

- **PCBA:** ~$150-185 per hub (Low volume run, 4-layer PCB)
- **Total Unit Cost:** ~$200-250 including enclosure
- **Optimization:** Shrinking PCB to <100x100mm can save ~$10/board on prototype runs.

12.20 Shared Equipment Bill of Materials

12.21 Connectors and Cables

Table 49: *Shared Cables and Connectors*

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

12.22 Test Equipment (Recommended)

Table 50: *Recommended Test Equipment*

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

12.23 Tools

Table 51: *Required 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

12.24 Consumables

Table 52: *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

12.25 Procurement Guide

12.26 Recommended Suppliers

12.26.1 Electronics

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

12.26.2 Mechanical

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

12.26.3 3D Printing

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

12.26.4 PCB Fabrication

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

12.27 Key Part Numbers Reference

Table 53: *Key Part Numbers for Major Suppliers*

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

12.28 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

12.29 Alternative Components

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

12.30 Coil Alternatives

Table 54: *Coil Component 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

12.31 ERT Ring Alternatives

Table 55: *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

12.32 Electronics Alternatives

Table 56: *Electronics Alternatives*

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

Note

For assembly procedures, see Section 15.1. For mechanical specifications, see Section 13.1. For electronics schematics, see Section 14.1.

13 Mechanical Design

13.1 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.

Hardware Documentation Reference

CAD files, manufacturing guides, and detailed drawings are maintained in the hardware documentation:

- **CAD Files:** `/hardware/cad/` - OpenSCAD source files and STL exports
- **Manufacturing Guide:** `/hardware/cad/docs/manufacturing-guide.md` - Printing settings and post-processing
- **Probe Assembly:** `/hardware/schematics/mechanical/probe-assembly.md` - Detailed assembly drawings
- **Rod Specifications:** `/hardware/schematics/mechanical/rod-specifications.md` - Material and dimensional specifications
- **ERT Ring Mounting:** `/hardware/schematics/mechanical/er-ring-mounting.md` - Electrode installation details

See `/hardware/cad/QUICKSTART.md` for getting started with the CAD files.

13.2 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.

13.3 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.

13.4 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 2.5-3.1 cm^2 ($\pi \times 1.0^2$ cm). At 3m depth, this creates only 0.75-0.93 liters of displacement per hole. In contrast, traditional 25mm rods requiring 50mm holes produce cross-sectional area of approximately 19.6 cm^2 ($\pi \times 2.5^2$ cm), displacing approximately 5.9 liters per hole at 3m depth. This represents a **6-7x reduction** in soil disturbance volume with the HIRT micro-probe design.

13.5 Key Dimensions

Table 57: *Key dimensional specifications for the HIRT micro-probe system.*

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

13.6 Rod Segments and Couplers

13.7 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.

Table 58: *Fiberglass rod specifications.*

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)

13.8 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.

13.9 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.

Table 59: *Thread specifications for modular connections.*

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)

13.10 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.

Table 60: *Ferrite core specifications.*

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

Table 61: *Coil winding specifications.*

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

13.11 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.

Table 62: *ERT ring electrode specifications.*

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 63: *Standard ERT ring mounting positions.*

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)

13.12 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.

Table 64: *Surface junction box specifications.*

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

13.13 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.

13.14 Manufacturing Procedures

13.15 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.

Table 65: *Recommended 3D printer settings for probe components.*

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

13.16 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

13.17 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.

13.18 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.

13.19 Advantages of Micro-Probe Design

Key advantages of the micro-probe design include:

- **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

13.20 Rapid Prototyping Guide

This section provides a streamlined workflow for building a **Minimum Viable Prototype (MVP)** to validate the probe design quickly. The goal is to achieve first functional data within 1-2 days, enabling rapid iteration if design changes are needed.

13.20.1 Prototyping Philosophy

The prototyping approach follows a "fail-fast" methodology:

- **Prioritize speed to first data** over production quality
- **Use relaxed tolerances** (+/-20% vs +/-10%) for initial validation
- **Accept reversible assembly** (dry-fit, no epoxy) for iteration
- **Focus on core physics validation** before manufacturing refinement

MVP Success Criteria (Relaxed for Prototyping)

Parameter	Production Spec	Prototype Target
Inductance	1.5 mH +/-10%	1.5 mH +/-20%
Q Factor @ 10kHz	>=30	>=15
Metal detection	Calibrated	Visible response
Thread quality	Production	Functional fit

If these relaxed criteria are met, proceed to production-quality builds.

13.20.2 Prototyping Workflow

The MVP build process consists of four main phases that can be completed in approximately 10-12 hours of active work over 2 days.

13.20.3 Minimum Parts List

For the MVP, only three 3D printed parts are required:

Table 67: *Minimum 3D printed parts for MVP prototype.*

Part	STL File	Purpose
Sensor body	`sensor_body_single_test.stl`	Houses coil
Male rod cap	`male_rod_cap_threads_test.stl`	Connects to rod
Probe tip	From `probe_tip_4x.stl`	Bottom terminator

Additional materials needed:

Table 68: *Additional materials for MVP prototype.*

Component	Specification	Notes
Fiberglass tube	16mm OD x 300mm	Single segment
Ferrite rod	8mm dia. x 100mm, NiZn	Core material
Magnet wire	34 AWG, 15m	For 300 turns
Test leads	Alligator clips	Bench testing

13.20.4 Coil Winding for Prototyping

The coil is the most critical component. Follow this simplified winding procedure optimized for first-time success.

Coil Winding Checklist:

- ☐ Clean ferrite rod with IPA
- ☐ Mark 50mm winding zone at center
- ☐ Leave 150mm wire tail, secure with tape
- ☐ Wind 300 turns, single layer, close-wound
- ☐ Maintain consistent light tension (~50g)
- ☐ **Measure inductance before securing** (target: 1.2-1.8 mH)
- ☐ Apply thin CA glue or nail polish to fix
- ☐ Strip and tin wire ends (5mm)

⚠ Critical: Measure Before Securing

Always verify inductance *before* applying fixative. If inductance is outside 1.2-1.8 mH, adjust turns (+/-20-30) and re-measure. Once glue is applied, changes are difficult.

13.20.5 Quick Functional Test Setup

The functional test validates that the coil responds to conductive targets. This is a qualitative "go/no-go" test before proceeding to full calibration.

Test Procedure:

1. Connect function generator to coil through 100 ohm series resistor
2. Set generator to 10 kHz sine wave, 2V peak-to-peak
3. Connect oscilloscope across the coil
4. Record baseline amplitude (no target present)
5. Slowly approach metal target (bolt, aluminum can) on non-metallic stick
6. Watch for amplitude or phase change on oscilloscope
7. Note distance at which change becomes visible

Pass Criteria:

- Stable baseline signal
- Visible change when metal target within 10cm
- Response repeatable across 3 trials

13.20.6 Prototype Test Decision Tree

After completing the functional test, use this decision tree to determine next steps.

Table 69: *Prototype test pass/fail criteria and remediation actions.*

Test	Pass Criteria	If Fail
Coil L, Q	L = 1.2-1.8 mH, Q >= 15	Re-wind coil, check core
Thread fit	Parts screw together	Reprint with blanks + tap/die
Metal detect	Visible response	Debug test setup, check drive

13.20.7 Troubleshooting Common Issues

No Signal on Oscilloscope

1. Check function generator output (probe directly)
2. Verify coil continuity with multimeter
3. Check all cable connections
4. Try higher drive voltage (up to 5V p-p)

No Response to Metal Target

1. Try larger target (bigger = stronger signal)
2. Try closer distance (<5cm)
3. Try different frequencies (2, 5, 20, 50 kHz)
4. Verify coil current is flowing (series resistor voltage)
5. Check for shorted turns (Q factor very low)

Threads Won't Fit

1. Chase with M12x1.75 tap (female) or die (male)
2. Light sanding on male thread OD
3. Check for debris or print defects
4. If cracking: reprint using blanks + tap/die approach

13.20.8 Next Steps After MVP Success

Once the MVP prototype passes all tests, proceed through these phases:

Table 70: *Prototype development phases after MVP validation.*

Phase	Goal	Key Tasks
Phase 2	Add ERT	Install electrode ring, test isolation
Phase 3	Multi-segment	Build 2-segment probe, test connection
Phase 4	Production wiring	Phoenix connectors, cable harness
Phase 5	Field test	Waterproof, deploy in soil

13.21 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).

14 Electronics and Circuits

14.1 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.

Hardware Documentation Reference

Complete circuit schematics and detailed design notes are maintained in the hardware documentation:

- **MIT Circuit:** `/hardware/schematics/electronics/mit-circuit.md` - Full TX/RX chain design with component values
- **ERT Circuit:** `/hardware/schematics/electronics/ert-circuit.md` - Howland current source and measurement circuits
- **Base Hub Circuit:** `/hardware/schematics/electronics/base-hub-circuit.md` - Central hub electronics integration
- **Block Diagrams:** `/hardware/schematics/electronics/probe-electronics-block.md` - System-level block diagrams

The diagrams in this section provide conceptual overviews; refer to the hardware schematics for exact component values and PCB layout guidance.

14.2 System Block Diagram

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.

14.3 MIT Transmit (TX) Chain

14.4 DDS Sine Generator

The transmit chain begins with a Direct Digital Synthesis (DDS) generator, the **AD9833**. This IC provides a highly precise sine wave output from 0.1 Hz to 12.5 MHz with 28-bit frequency resolution. Its compact MSOP-10 footprint and low power consumption make it ideal for the 2-50 kHz HIRT operating range.

Table 71: *AD9833 DDS Generator Specifications.*

Parameter	Specification
Part Number	**AD9833BRMZ**
Frequency Range	0 Hz to 12.5 MHz
Output Level	0.6 V p-p sine wave
Interface	SPI (3-wire)
Resolution	28-bit frequency, 12-bit phase
Power Supply	2.3-5.5V, 12.65 mW typical

14.5 TX Power Driver

The DDS output is buffered by a **Texas Instruments OPA2186** precision operational amplifier. This component is selected for its zero-drift architecture and ultra-low quiescent current (**90 μA**), which ensures high precision and extended battery life for the hub while maintaining rail-to-rail output for the TX coil drive.

Table 72: *TX Driver Op-Amp Specifications.*

Parameter	OPA2186 Specification
Quiescent Current	**90 μA**
Drift	**0.04 μV/°C** (Zero-Drift)
Offset Voltage	10 μV

Parameter	OPA2186 Specification
Power Supply	4.5V to 36V

14.6 MIT Receive (RX) Chain

14.7 RX Preamplifier (AD8421)

The receiver front-end utilizes the **Analog Devices AD8421**. This high-speed instrumentation amplifier features an exceptionally low input voltage noise floor of **3 nV/$\sqrt{\text{Hz}}$**. This performance characteristic is essential for resolving the weak secondary magnetic fields generated by subsurface targets in the MIT tomography process.

Table 73: *RX Preamplifier Specifications.*

Parameter	Specification
Component	**AD8421**
Input Noise	**3 nV/$\sqrt{\text{Hz}}$**
Bandwidth (G=10)	10 MHz
Slew Rate	35 V/μs
Supply Current	2.0 mA

14.7.1 Noise Floor Measurement Conditions

The AD8421's specified noise floor of **3 nV/$\sqrt{\text{Hz}}$** is achieved under specific measurement conditions. Field performance depends on several factors:

Table 74: *Noise floor measurement conditions and field impact.*

Condition	Specification	Field Typical	Impact on SNR
Bandwidth	1-50 kHz (HIRT operating range)	2-50 kHz	~100 nV RMS integrated
Temperature	25°C reference	-10 to +40°C	±10% variation
Cable length	<1 m bench test	3-5 m probe cable	+20-50% noise pickup
Averaging	100-sample mean	16-64 samples typical	Improves by $\sqrt{N}$

Integrated Noise Calculation: For a 1-50 kHz bandwidth (49 kHz span), the theoretical integrated input-referred noise is:

$$V_{n,rms} = 3 \text{ nV}/\sqrt{\text{Hz}} \times \sqrt{49,000 \text{ Hz}} \approx 100 \text{ nV RMS}$$

This represents the *design target* under controlled conditions. Field measurements typically show 150-300 nV RMS due to cable capacitance, EMI pickup, and connector losses.

i Performance Claim Context

The ~100 nV noise floor is a **design target** based on component specifications and bench measurements. Actual field performance varies with environmental conditions and cable routing. For planning purposes, assume 200-300 nV RMS input-referred noise in typical outdoor conditions.

14.8 Signal Conditioning and Gain Stage

Following the AD8421 preamplifier, the signal passes through additional gain and filtering stages before reaching the ADC. An instrumentation amplifier (INA128) provides adjustable gain to match signal levels to the ADC input range. The total signal chain gain is typically 800-1000x, bringing microvolt-level coil signals up to the millivolt range required by the ADC.

14.9 Signal Level Progression

14.10 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.

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.

14.11 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);
```

14.12 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.

Table 75: *ERT Current Source Specifications.*

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)

14.12.1 Compliance Voltage vs Load

The +/-10V compliance voltage determines the maximum load impedance at each current setting. Operators should select current levels based on expected soil resistivity to ensure adequate measurement headroom:

Table 76: *ERT current vs load compliance limits. Higher resistivity soils require lower current to stay within compliance voltage.*

Max Current	Max Load at 10V	Typical Application
2.0 mA	5 k-ohm	Low resistivity soil (<100 ohm-m)
1.0 mA	10 k-ohm	Medium resistivity (100-500 ohm-m)
0.5 mA	20 k-ohm	High resistivity (>500 ohm-m)

Compliance Limit Warning

If the load impedance exceeds the compliance limit for the selected current, the current source will saturate and actual injected current will be less than commanded. The ERT firmware monitors this condition and flags affected measurements. Reduce current setting or improve electrode contact if compliance warnings occur frequently.

14.13 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.

14.14 ADC Interface

Table 77: *ADS1256 ADC Specifications.*

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

14.15 Multiplexer Switching

With up to 24 probes in a typical array, the HIRT system requires a scalable multiplexing strategy. The design uses **CD74HC4067** 16:1 analog multiplexers controlled by MCU GPIO pins. Each TX and RX signal path has its own multiplexer, allowing independent selection of transmit and receive probes. For arrays exceeding 16 probes, cascaded multiplexers can be used.

14.16 Power Distribution

Table 78: *Power Rail Specifications.*

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

14.17 Noise Filtering Stages

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

14.18 Shielding and Ground Loop Prevention

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

14.19 PCB Layout Guidelines

14.20 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

14.21 Key Component Summary

Table 79: *Key IC Components.*

Component	Part Number	Function	Package
DDS	AD9833BRMZ	Signal generator	MSOP-10
TX Driver	OPA454AIDDAR	Coil driver	SOIC-8
Preamp	AD8421BRZ	RX preamplifier	SOIC-8
Inst Amp	INA128PAG4	Gain stage	DIP-8
ADC	ADS1256IDBR	24-bit ADC	SSOP-28
Multiplexer	CD74HC4067M	16-channel mux	SOIC-24
MCU	ESP32-WROOM-32	Controller	Module
V-Reference	REF5025AIDGKR	2.5V reference	SOIC-8
LDO	AMS1117-3.3	3.3V regulator	SOT-223

14.22 Connector Pinouts (Probe-to-Zone)

Table 80: *12-pin Probe Connector Pinout.*

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

14.23 Firmware Status

Firmware Development - Phase 2

The hardware system documented in this whitepaper requires MCU firmware to operate. Firmware development is explicitly **Phase 2** of the project, separate from the hardware design presented here.

Current Status:

- Hardware is designed for ESP32-WROOM-32 MCU
- No firmware repository is published yet
- Planned firmware features: DDS control, ADC sampling, lock-in detection, USB data logging

Planned Repository: `github.com/hirt-project/hirt-firmware` (future)
Builders can test hardware subsystems (coils, ERT source, ADC) using bench equipment before firmware is available. See Section 18 for the software development roadmap.

14.24 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

14.25 Troubleshooting Guide

Table 81: *Common Issues and Solutions.*

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

14.26 References

1. Analog Devices. AD9833 Programmable Waveform Generator Data Sheet. Rev. F, 2019. Datasheet
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15 Assembly and Wiring

15.1 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.

> Hardware Documentation Reference
>
> Detailed assembly drawings and wiring diagrams are maintained in the hardware documentation:
> - **Assembly Drawings:** `/hardware/drawings/assembly-drawings.md` - Visual assembly guides
> - **Probe Head Drawing:** `/hardware/drawings/probe-head-drawing.md` - Detailed probe head construction
> - **Probe Assembly:** `/hardware/schematics/mechanical/probe-assembly.md` - Step-by-step mechanical assembly
> - **Manufacturing Notes:** `/hardware/cad/docs/manufacturing-notes.md` - 3D printing tips and troubleshooting
>
> These hardware docs contain the most current assembly procedures and are updated as the design evolves.

15.2 Parts List

15.2.1 Printed Parts (PETG/ASA)

Table 82: *3D-printed probe components*

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

15.2.2 Hardware

Table 83: *Hardware and consumable materials*

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

15.3 Tools Required

Table 84: *Essential tools for assembly*

Tool	Purpose
Hacksaw or Tube Cutter	Cutting fiberglass tubing
400-grit Sandpaper	Surface preparation
M12x1.75 Tap	Threading female parts

Tool	Purpose
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

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

15.4 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.

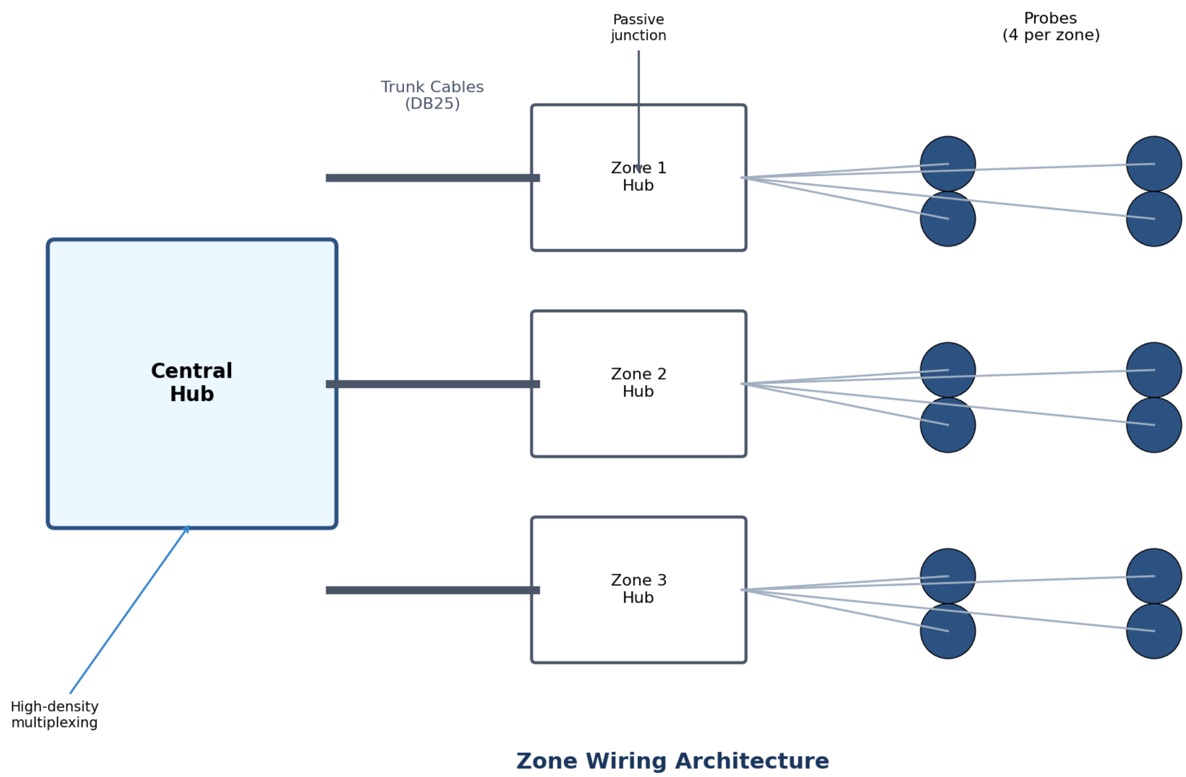


Figure 13: *Zone wiring architecture showing probe groupings, zone boxes, and trunk cable routing to the central hub. Each zone aggregates 4 probes through a passive junction box.*

15.4.1 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

15.4.2 Wiring Harness Layout

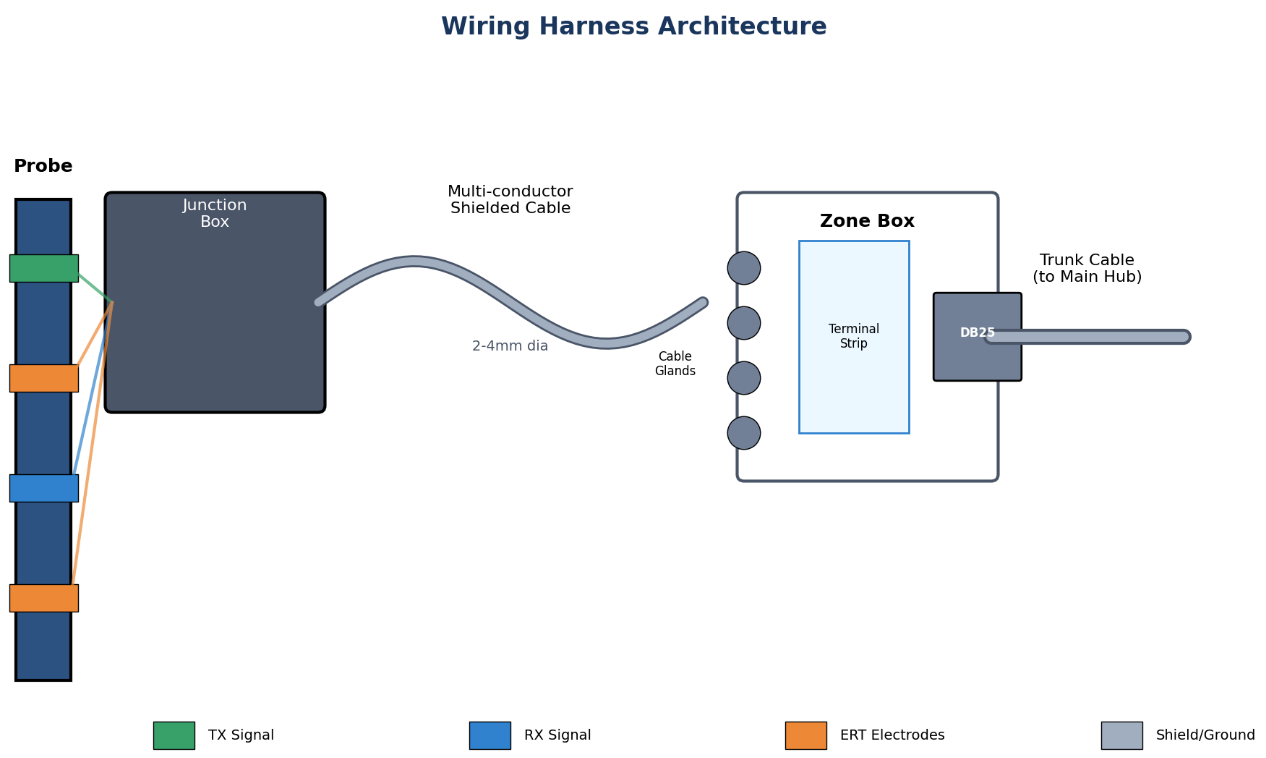


Figure 14: *Wiring harness architecture from probe sensors through junction box and zone box to the main hub. The multi-conductor shielded cable (2-4mm diameter) carries all sensor signals.*

15.4.3 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.

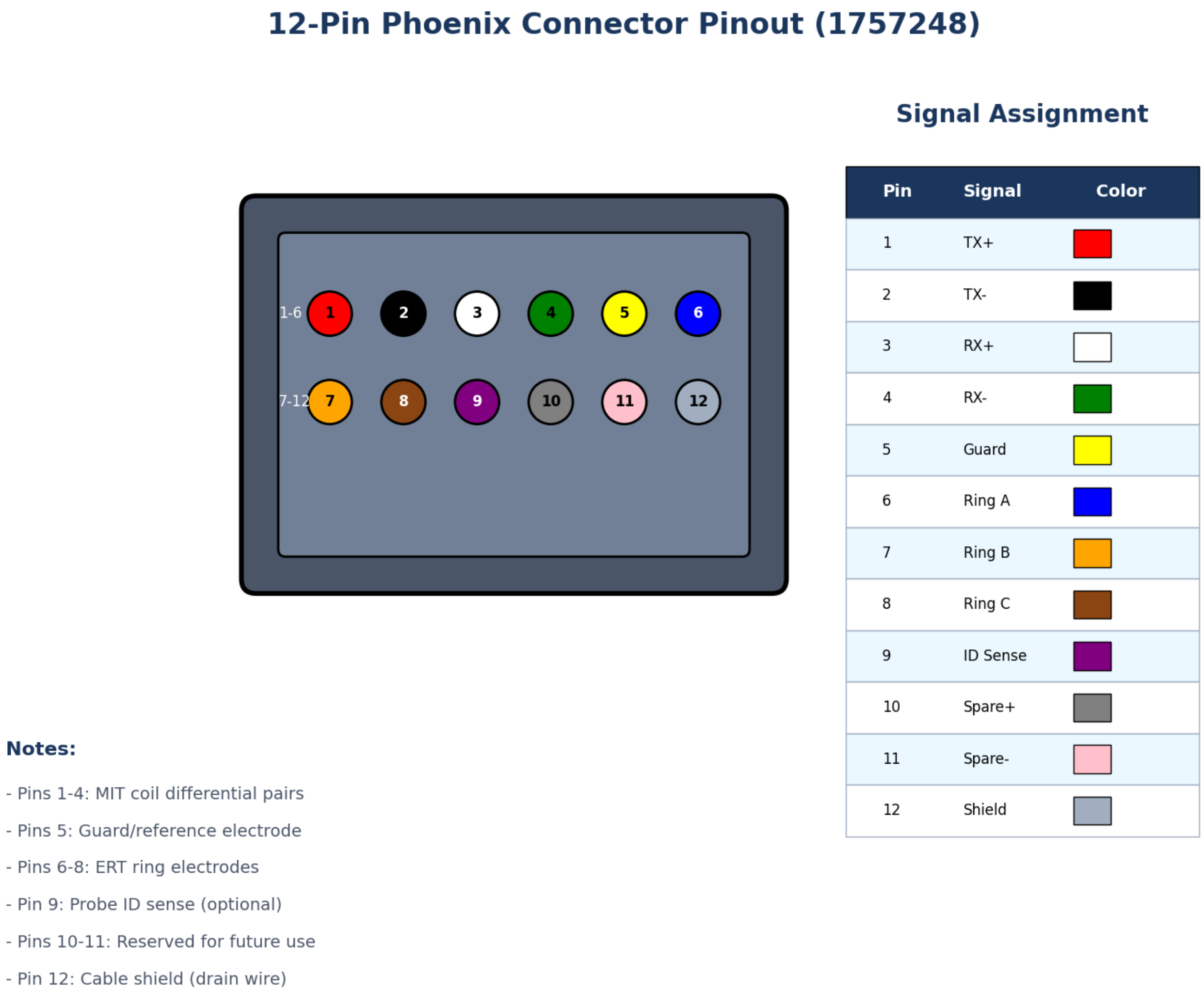
15.5 Assembly Procedures

15.5.1 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

15.5.2 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.



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	

Figure 15: *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.*

ℹ 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

15.5.3 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.

15.6 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.

15.6.1 Backplane Functional Zones

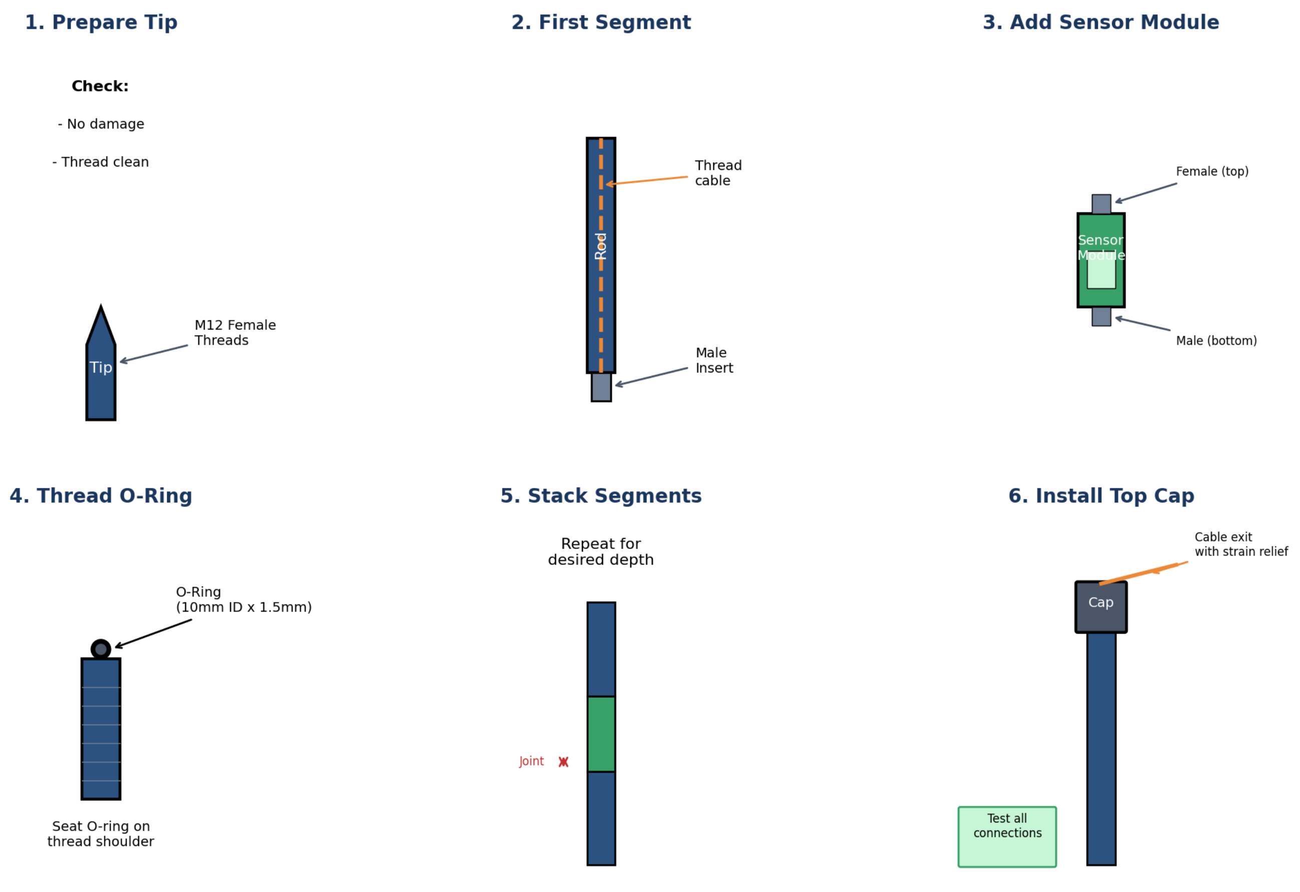


Figure 16: *Six-step assembly sequence: (1) Prepare probe tip, (2) Thread cable through first segment, (3) Add sensor module, (4) Seat O-ring on thread shoulder, (5) Stack additional segments, (6) Install top cap with cable strain relief.*

Table 85: *Backplane PCB functional zones*

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

15.7 Quality Checks

15.7.1 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)

15.7.2 After Complete Assembly

Mechanical Checks:

- Total length correct for intended depth

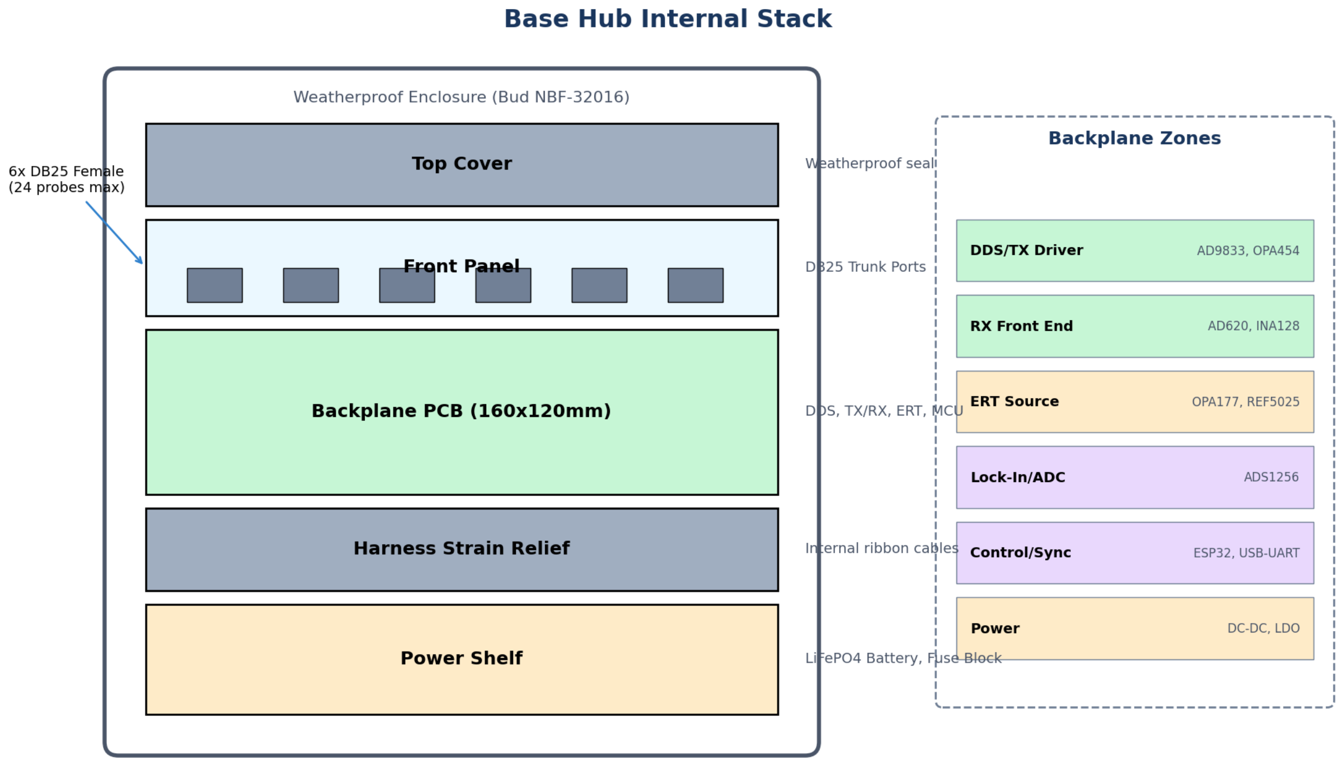


Figure 17: *Base hub internal stack layout showing the layered architecture from power shelf at bottom to weatherproof cover at top. The backplane PCB contains all analog and digital circuits.*

- 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

15.8 Troubleshooting

15.8.1 Thread Issues

Table 86: *Thread issue troubleshooting guide*

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

15.8.2 Electrical Issues

Table 87: *Electrical issue troubleshooting guide*

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

15.9 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

15.10 Post-Assembly

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

1. Complete Testing Procedures (Section 16.1)
2. Complete Calibration Procedures (Section 17.1)
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

16 Testing and Verification

16.1 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

16.2 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.

16.2.1 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

16.3 Pre-Testing Setup

16.3.1 Test Equipment Required

Table 88: *Test equipment requirements for HIRT probe verification*

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

16.3.2 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

16.4 Mechanical Tests

16.4.1 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.

16.4.2 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

16.4.3 Test M3: ERT Ring Mounting

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

Table 89: *ERT ring position specifications*

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

16.4.4 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.

16.5 Electrical Tests

16.5.1 Test E1: Power Supply Verification

Purpose: Verify power input and regulation circuits function correctly.

Table 90: *Power supply test criteria*

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

16.5.2 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.

16.5.3 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).

16.6 MIT Subsystem Tests

16.6.1 Test MIT1: Coil Parameters

Table 91: *MIT coil parameter measurements. Q factor specification references calibration section (Section 17.1) for frequency-dependent targets.*

Parameter	TX Coil	RX Coil	Pass Criteria
Inductance	Measured: ____	Measured: ____	1-2 mH
Q Factor @ 10 kHz	Measured: ____	Measured: ____	≥ 30
DC Resistance	Measured: ____	Measured: ____	< 8 ohm
Coil Isolation	N/A	N/A	> 1 M ohm

16.6.2 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.

16.6.3 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.

16.6.4 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).

16.6.5 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.

16.7 ERT Subsystem Tests

16.7.1 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.

16.7.2 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.

16.7.3 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.

16.7.4 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.

16.8 System Integration Tests

16.8.1 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.

16.8.2 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.

16.8.3 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.

16.9 Quantitative Validation Protocols

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

16.9.1 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).

$$\text{MAPE} = \frac{1}{n} \sum \frac{|R_{\text{measured}} - R_{\text{true}}|}{R_{\text{true}}} \times 100\%$$

Target: MAPE $<$ 1.0% across the dynamic range.

16.9.2 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.

16.9.3 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).

16.10 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

Table 92: *QC test category summary*

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

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

16.11 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

Tip

For calibration procedures, see Section 17.1. For troubleshooting guidance when tests fail, see Section 11.1.

17 Calibration

17.1 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.

17.2 Calibration Principles

17.2.1 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

17.2.2 Key Parameters and Tolerances

Table 93: *Calibration parameters and acceptance tolerances*

Parameter	Target	Tolerance	Measurement Freq
Coil Inductance	1.5 mH	+/-10%	1 kHz
Coil Q Factor @ 2 kHz	>=25	Minimum	2 kHz
Coil Q Factor @ 10 kHz	>=30	Minimum	10 kHz
Coil Q Factor @ 50 kHz	>=20	Minimum	50 kHz
Coil DC Resistance	<8 ohm	Maximum	DC
Self-Resonant Freq	>200 kHz	Minimum	VNA sweep
TX-RX Coupling	<-40 dB	Maximum	10 kHz
DDS Frequency	Commanded	+/-1%	All
TX Amplitude	Design spec	+/-10%	All
RX Gain	Design spec	+/-10%	All
ERT Current	Commanded	+/-5%	DC
Reciprocity	A->B = B->A	+/-5%	All

17.2.3 Expected Data Error Thresholds

Based on published practices in the geophysical literature (SimPEG, pyGIMLi), the following measurement repeatability thresholds establish pass/fail criteria for quality control:

Table 94: *Expected measurement error thresholds for QC pass/fail determination*

Measurement Type	Expected Error	QC Threshold	Notes
MIT amplitude	3-5%	<5%	Relative measurement-to-measurement
MIT phase	2-3 deg	<5 deg	Absolute phase accuracy
ERT resistance	3-5%	<5%	Relative error typical for DC resistivity
Reciprocity	<3%	<5%	A->B vs B->A difference

These thresholds are consistent with standard inversion software defaults (e.g., pyGIMLi uses 3% relative error for ERT; SimPEG recommends 5-10% data uncertainty for DC resistivity). Measurements exceeding these thresholds should be flagged for review and potential re-acquisition.

17.3 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).

17.4 Required Equipment

Table 95: *Required calibration 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

17.4.1 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

17.5 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.

17.6 Coil Calibration Procedures

17.6.1 TX Coil Inductance

1. Connect LCR meter to TX coil leads (ensure proper polarity)
2. Set measurement frequency to 1 kHz (reference frequency)
3. Measure inductance (L) and record in mH
4. Compare to specification: target 1.5 mH, tolerance +/-10% (1.35-1.65 mH)
5. Record Pass/Fail status on calibration sheet

17.6.2 TX Coil Q Factor (Multi-Frequency)

The Q factor must be measured across the full operating frequency range:

Frequency	Minimum Q	Notes
2 kHz	>=25	Deep penetration mode
10 kHz	>=30	Primary operating frequency
50 kHz	>=20	High-resolution mode

Procedure:

1. Using same LCR meter setup as inductance measurement
2. Measure Q factor at 2 kHz, 10 kHz, and 50 kHz
3. Alternatively, calculate: $Q = (2\pi fL)/R$ where R is the measured ESR
4. All three frequency points must pass minimum Q thresholds
5. Low Q indicates: winding issues, wrong core material, excessive self-capacitance, or core saturation

Self-Resonant Frequency Check:

If VNA available, sweep 100 kHz - 1 MHz to identify the self-resonant frequency (SRF). Target: SRF > 200 kHz. If SRF falls within operating range (2-50 kHz), the coil must be rewound with single-layer technique to reduce parasitic capacitance.

17.6.3 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.

17.7 TX Chain Calibration

17.7.1 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.

$$\text{Error (\%)} = \frac{f_{\text{actual}} - f_{\text{commanded}}}{f_{\text{commanded}}} \times 100$$

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

17.7.2 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)

17.8 RX Chain Calibration

17.8.1 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.

17.8.2 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

17.9 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.

17.9.1 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

17.9.2 Reciprocity Verification

Reciprocity checks are essential for validating measurement quality. For both MIT and ERT, swapping transmitter and receiver should yield equivalent measurements within error bounds:

$$\frac{|M_{A\to B} - M_{B\to A}|}{(M_{A\to B} + M_{B\to A})/2} \times 100\% < 5\% \tag{1}$$

where M represents the measured quantity (voltage ratio for MIT, apparent resistivity for ERT).

Reciprocity Check Protocol

1. Measure forward path (A transmit -> B receive)
2. Measure reciprocal path (B transmit -> A receive)
3. Calculate percent difference using Equation 1
4. Flag measurements exceeding 5% for investigation
5. Common causes of poor reciprocity: loose connections, electrode corrosion, coupling variations

Systematic reciprocity errors indicate calibration drift or hardware issues. Random reciprocity failures suggest environmental noise or poor electrode contact. The pyGIMLi crosshole ERT examples recommend filtering data points with reciprocal error exceeding 5% before inversion.

17.10 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.

17.11 ERT Calibration

17.11.1 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.

17.11.2 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

17.12 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).

Table 97: *Typical uncertainty budget for HIRT measurements*

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)

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

$$\text{Measurement} = X \pm 2\sigma$$

17.13 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

17.14 Recalibration Schedule

Table 98: *Recalibration schedule triggers and actions*

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

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).

17.15 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

18 Validation

18.1 Overview

This section documents validation protocols for verifying HIRT system performance against design specifications. Validation ensures that a newly constructed system meets the requirements for field deployment and provides traceable evidence for HardwareX journal compliance.

Documentation Status

This section contains **Target specifications** that define expected performance. Measured validation data will be added as bench testing is completed. Specifications marked **(Target)** have not yet been validated against physical hardware.

18.2 Validation vs. Testing

Testing (see Testing & Verification) confirms that individual components and assemblies function correctly during the build process.

Validation confirms that the complete, integrated system achieves the performance specifications required for its intended use cases.

Aspect	Testing	Validation
Scope	Components, subsystems	Complete system
Question	Does it work?	Does it work well enough?
Criteria	Pass/fail functional checks	Quantitative performance metrics
Timing	During build	After build, before deployment

18.3 System-Level Specifications

18.3.1 MIT-3D Channel

Parameter	Target	Method	Status
Operating frequencies	2, 5, 10, 20, 50 kHz	Frequency sweep test	(Target)
TX coil current	10 ± 1 mA RMS	Oscilloscope measurement	(Target)
RX noise floor	< 100 nV/rt-Hz at 10 kHz	Spectrum analyzer	(Target)
Dynamic range	> 80 dB	Calibration target test	(Target)
Phase accuracy	± 0.5°	Lock-in verification	(Target)
Inter-probe consistency	< 5% amplitude variation	Cross-calibration	(Target)

18.3.2 ERT-Lite Channel

Parameter	Target	Method	Status
Injection current	0.5, 1.0, 2.0 mA selectable	Multimeter measurement	(Target)
Current accuracy	± 2% of setpoint	Precision resistor test	(Target)
Voltage measurement range	0.1 mV - 10 V	Calibration resistor	(Target)
Input impedance	> 10 Mohm	Impedance meter	(Target)
Reciprocity error	< 3% (typical soil)	Field reciprocity check	(Target)
Contact resistance tolerance	Up to 10 kohm	Simulated contact test	(Target)

18.3.3 Mechanical

Parameter	Target	Method	Status
Probe water resistance	IP67 (1 m, 30 min)	Submersion test	(Target)
Connector cycles	> 500 insertions	Lifecycle test	(Target)
Operating temperature	-10°C to +50°C	Environmental chamber	(Target)
Drop resistance	1 m onto concrete	Drop test	(Target)

18.4 Validation Procedures

18.4.1 MIT-3D Validation Protocol

Equipment Required:

- Calibrated oscilloscope (100 MHz bandwidth or greater)
- Signal generator with frequency counter
- Precision current shunt (0.1%, 10 ohm)
- Faraday cage or shielded enclosure
- Reference calibration targets (aluminum spheres: 5, 10, 25 mm diameter)

Procedure:

1. **Baseline Noise Measurement**
   - Place probe assembly in shielded enclosure
   - Record RX noise spectrum at each operating frequency
   - Verify noise floor < 100 nV/rt-Hz specification
2. **TX Current Verification**
   - Insert precision shunt in TX coil circuit
   - Measure RMS current at each frequency
   - Verify 10 ± 1 mA across operating range
3. **Phase Accuracy Test**
   - Apply known reference signal to RX path
   - Measure reported phase vs. true phase
   - Verify ± 0.5° accuracy
4. **Dynamic Range Test**
   - Position calibration spheres at known distances
   - Measure response from maximum (5 mm at 0.1 m) to minimum detectable
   - Calculate and verify > 80 dB dynamic range
5. **Cross-Probe Calibration**
   - Use identical calibration target at identical position
   - Measure response from each probe
   - Verify < 5% variation after calibration factor application

18.4.2 ERT-Lite Validation Protocol

Equipment Required:

- Calibrated multimeter (6-digit resolution)
- Precision resistor set (0.1%: 10 ohm, 100 ohm, 1 kohm, 10 kohm)
- Variable resistance decade box
- Soil simulation circuit (parallel RC network)

Procedure:

1. **Current Source Accuracy**
   - Connect precision 100 ohm resistor
   - Measure actual injected current at each setpoint
   - Verify ± 2% accuracy
2. **Voltage Measurement Linearity**
   - Apply known voltages across measurement range
   - Compare reported values to reference meter
   - Verify linearity < 0.5% of full scale
3. **Contact Resistance Tolerance**
   - Insert series resistance (0, 1 kohm, 5 kohm, 10 kohm) in current path
   - Verify current regulation maintains accuracy
   - Document measurement error vs. contact resistance
4. **Reciprocity Bench Test**
   - Use resistor network simulating soil
   - Measure forward and reverse transfer impedance
   - Verify < 1% bench reciprocity error

18.4.3 Integrated System Validation

Test Tank Protocol:

For systems with access to a controlled test tank:

1. Fill tank with uniform conductivity solution (e.g., 500 μS/cm)
2. Deploy 4-probe minimum configuration
3. Insert calibration target (metal sphere, PVC cylinder) at known position
4. Acquire MIT and ERT data

5. Process through standard inversion workflow
6. Verify target localization accuracy (position, depth)

Target Specifications:

Parameter	Target	Method
Lateral localization	$\pm$ 0.5 $\times$ probe spacing	Known target test
Depth localization	$\pm$ 0.25 m	Known target test
Size estimation	Within 2$\times$ actual	Known target test

18.4.4 Field Validation

Protocol for First Deployment:

1. Select site with known buried target (test installation)
2. Deploy full probe array
3. Acquire complete MIT + ERT dataset
4. Process and compare to known target position
5. Document any discrepancies

Acceptance Criteria:

- All probes communicate successfully
- Reciprocity error $< 5\%$ in field conditions
- Known target detected and localized within specifications
- No hardware failures during 4-hour continuous operation

18.5 Validation Records

For HardwareX compliance, maintain documentation including:

1. **Calibration Certificates** for all test equipment
2. **Raw Validation Data** (oscilloscope captures, meter readings)
3. **Calculated Performance Metrics** with uncertainty estimates
4. **Pass/Fail Determination** for each specification
5. **Corrective Actions** if specifications not met

18.5.1 Record Template

```
HIRT Validation Record
======================
System Serial Number: _______________
Validation Date: _______________
Operator: _______________

MIT-3D Channel
--------------
Noise Floor: _______ nV/rt-Hz (Target: < 100)  [PASS/FAIL]
TX Current: _______ mA RMS (Target: 10 ± 1)  [PASS/FAIL]
Phase Accuracy: _______ ° (Target: ± 0.5)    [PASS/FAIL]
Dynamic Range: _______ dB (Target: > 80)     [PASS/FAIL]

ERT-Lite Channel
----------------
Current Accuracy: _______% (Target: ± 2%)    [PASS/FAIL]
Reciprocity Error: _______% (Target: < 3%)   [PASS/FAIL]
Contact Tolerance: _______ kohm (Target: 10)   [PASS/FAIL]

Integrated System
-----------------
```

```
Localization Accuracy: _______ m            [PASS/FAIL]
Continuous Operation: _______ hours         [PASS/FAIL]

Overall Validation: [PASS/FAIL]

Notes: _____________________________________________________
Operator Signature: ________________________________________
```

18.6 Revalidation Requirements

Revalidate the system after:

- Major firmware updates
- Component replacement affecting measurement path
- Physical damage to probes or electronics
- Extended storage (> 12 months)
- Any unexplained measurement anomalies

Annual revalidation is recommended for systems in regular use.

Part IV
Theory

19 Physics Theory

19.1 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.

19.2 MIT-3D (Low-Frequency Electromagnetic)

19.2.1 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.

19.2.2 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

Table 104: *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.*

Target Depth	Recommended Frequencies	Integration Time
0.5-1.5 m (shallow)	20-50 kHz	1-3 sec

Target Depth	Recommended Frequencies	Integration Time
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

19.3 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:

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \tag{2}$$

where $\omega = 2\pi f$ is the angular frequency, $\mu = \mu_0\mu_r$ is the magnetic permeability (typically $\mu_0 = 4\pi \times 10^{-7}$ H/m for non-magnetic soils), and σ is the electrical conductivity in S/m.

For practical field calculations, this simplifies to:

$$\delta \approx 503\sqrt{\frac{\rho}{f}} \text{ meters} \tag{3}$$

where ρ is resistivity in ohm-meters and f is frequency in Hz. This approximation assumes non-magnetic soil ($\mu_r = 1$).

Example: At 10 kHz in 100 Ω·m soil: $\delta \approx 503\sqrt{100/10000} = 503 \times 0.1 = 50.3$ m. This confirms that skin depth is not the limiting factor for HIRT at typical operating frequencies and soil conditions.

Table 105: *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.*

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

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

19.4 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.

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

19.4.1 SNR Optimization

Signal-to-noise ratio (SNR) for MIT measurements depends on several controllable factors:

$$\text{SNR} \propto D_m^{3/2} \times I \times \sqrt{t_{int}} \tag{4}$$

where D_m is coil diameter, I is transmit current, and t_{int} is integration time.

Key optimization strategies:

- **Coil diameter**: The most important factor—SNR scales as $D_m^{3/2}$. Doubling coil diameter increases SNR by ~2.8x
- **Integration time**: Provides linear improvement with square root of time—4x longer integration yields 2x SNR improvement
- **Transmit current**: Linear relationship—doubling current doubles SNR (within thermal limits)

The depth of investigation (DOI) has a modest relationship with noise floor: DOI $\propto$ noise$^{-0.2}$. Reducing noise by a factor of 10 extends DOI by approximately 1.6x. This relationship reinforces that geometric factors (probe depth and spacing) remain the primary determinants of investigation depth.

19.5 ERT-Lite (Galvanic Method)

19.5.1 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.

19.5.2 Geometric Factor K

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

$$\rho_a = K \times \frac{V}{I} \tag{5}$$

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

$$K \approx \pi \times L \tag{6}$$

where L is the separation distance between current injection electrodes.

i Derivation of K = piL for Crosshole Ring Electrodes

The simplified $K \approx \pi L$ relationship for HIRT assumes:

1. **Cylindrical symmetry:** Current flows radially outward from ring electrodes into a homogeneous half-space
2. **Ring electrode approximation:** Each ring acts as a line source at depth, with current density uniform around the ring circumference
3. **Infinite medium correction:** The 2π factor for full-space reduces to π for practical borehole measurements where current primarily flows laterally through the formation between probes
4. **Potential electrode at midpoint:** Voltage is measured at the potential electrode(s) located between or adjacent to current electrodes

For a two-electrode (pole-pole) configuration with current injection at ring A and return at ring B separated by distance L, the potential difference measured at a ring between them follows: $V \approx \frac{I\rho}{\pi L}$, yielding $K \approx \pi L$.
This approximation is valid within +/-15% for typical HIRT geometries (L = 0.5-2.5 m, ring width « L). More accurate geometric factors can be computed numerically for specific electrode arrangements using finite element modeling.

Table 106: *ERT geometric factors for HIRT ring electrode configurations. Larger electrode separations provide greater depth of investigation but lower resolution.*

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

19.5.3 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)

19.6 Multi-Frequency Response

Different subsurface features exhibit characteristic frequency-dependent responses that enable target discrimination. The frequency response of metallic targets depends on both target size and material conductivity: larger targets and higher-conductivity metals (copper, aluminum) show stronger low-frequency responses, while smaller targets require higher frequencies for adequate skin depth penetration into the metal volume. Non-metallic soil disturbances and moisture contrasts show broader, less frequency-dependent signatures that help distinguish them from metal.

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

19.7 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 and the resulting illumination angles.

19.7.1 Surface vs. Crosshole: A Medical Analogy

The distinction between surface and crosshole geophysics parallels the difference between medical X-ray imaging and CT scanning. A single X-ray provides a 2D projection of 3D anatomy—all structures along the ray path collapse into a single shadow. Computed tomography (CT) surrounds the patient with detectors, acquiring projections from hundreds of angles to reconstruct true 3D anatomy.

Surface geophysical methods operate like X-rays: all sensors are above the target, looking downward. They measure the integrated response along a single dominant direction. A target at 2 m depth produces nearly the same surface signature whether it sits at 1.8 m or 2.2 m depth—vertical resolution is inherently poor because all ray paths travel steeply through the target zone.

Crosshole tomography operates like CT scanning: probes surround the target volume, acquiring measurements from many angles. A target at 2 m depth is illuminated horizontally, diagonally, and from below by ray paths connecting different probe pairs. This angular diversity enables true 3D reconstruction with isotropic resolution—the ability to distinguish targets separated by similar distances horizontally or vertically.

This is not merely an improvement in data processing; it is a fundamental physics advantage driven by measurement geometry. You cannot compute tomography from surface data because the ray paths lack angular diversity. Crosshole geometry provides that diversity by design.

19.7.2 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. More critically, nearly all energy travels vertically through the target, providing excellent lateral resolution but poor vertical discrimination.

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 (*theoretical advantage based on ray coverage geometry; field validation pending*), with approximately isotropic resolution in all three dimensions.

19.7.3 Illumination Angles and Angular Diversity

The fundamental advantage of crosshole geometry lies in angular diversity—the range of angles from which energy interrogates the target. Surface methods illuminate targets from a narrow cone of angles (typically 60-80 degrees from vertical), while crosshole methods provide illumination from nearly all directions in the horizontal plane and many angles in the vertical plane.

Consider a 0.5 m diameter spherical target at 2.5 m depth in a 3-probe HIRT array with 2 m spacing. The target experiences:

- **12 unique ray paths** between probe pairs (3 probes * 4 measurement depths * 2 channels = 24 measurement geometries)
- **Angular coverage** spanning 180 degrees in horizontal plane
- **Vertical angles** from -45 to +45 degrees relative to target center

This angular diversity directly translates to reconstruction quality. Tomographic inversion requires measurements that sample the target from multiple perspectives. A general rule: resolution improves linearly with the number of independent viewing angles up to approximately 20-30 angles, after which diminishing returns occur.

Figure Concept: Illumination angle comparison diagram

A side-by-side comparison showing ray path angles for surface vs. crosshole geometry:

Left panel (Surface ERT/MIT): - Show 5-7 surface sensors arranged in a line above ground - Draw ray paths from each sensor down to a target at 2.5 m depth - All rays converge downward in a narrow cone (60-80 deg from vertical) - Color-code rays by angle: steep (red), moderate (orange), shallow (yellow) - Annotate: "All rays from above - poor vertical resolution"

Right panel (HIRT Crosshole): - Show 3 probes at 2 m spacing inserted to 3 m depth - Draw ray paths connecting probes at multiple depths through a target at 2.5 m - Include horizontal rays (green), ascending rays (blue), descending rays (purple) - Show angular coverage: 180 deg horizontal, +/- 45 deg vertical - Annotate: "Rays from all directions - isotropic 3D resolution"

Bottom comparison: - Small polar plot for each showing angular coverage - Surface: narrow wedge (60-80 deg) - Crosshole: nearly full circle coverage

Scale: use consistent 1 m grid spacing. Target shown as 0.5 m sphere at 2.5 m depth.

Type: diagram

Surface methods concentrate their ray paths in the vertical direction. A Wenner array with 1 m electrode spacing samples the subsurface primarily along near-vertical current paths. The resulting sensitivity pattern is pancake-shaped: excellent lateral resolution but poor depth discrimination. Targets at 2.0 m vs. 2.5 m depth may show <10% difference in measured apparent resistivity.

Crosshole methods distribute ray paths across many angles. The sensitivity pattern is approximately spherical around each probe, with maximum sensitivity along the direct probe-to-probe lines. Targets at 2.0 m vs. 2.5 m depth show >50% difference in affected ray paths, enabling confident depth determination.

19.7.4 Resolution Comparison: Surface vs. Crosshole

The following table quantifies the resolution advantage of crosshole geometry at depth. Resolution is defined as the minimum separation at which two point targets can be distinguished with >80% confidence in inverted models.

Table 107: *Resolution comparison across geophysical methods at typical HIRT investigation depths. Note that HIRT provides approximately isotropic resolution (similar in all directions), while surface methods show 3-6x worse vertical than lateral resolution.*

Method	Lateral Resolution	Vertical Resolution	Resolution at 3 m Depth	Depth Limit
Surface Magnetometry	1-2 m	Poor (>3 m)	~2 m lateral	3-4 m (ferrous only)
GPR (100 MHz)	0.3-0.5 m (shallow)	0.05-0.1 m (shallow)	>1 m (clay absorbs signal)	0.5-2 m in clay
Surface ERT (Wenner)	~1x spacing	~0.5x spacing	2-3 m lateral	4-6 m
EM31/CMD	1-2 m	Poor (>3 m)	~2 m lateral	3-5 m (conductive)
HIRT Crosshole MIT	**0.5-1x spacing**	**0.3-0.5x spacing**	**0.75-1.5 m (isotropic)**	**3-4 m**
HIRT Crosshole ERT	**0.5-1x spacing**	**0.3-0.5x spacing**	**0.75-1.5 m (isotropic)**	**3-5 m**

The key distinction is **isotropic vs. anisotropic resolution**. Surface methods provide good lateral resolution but poor vertical resolution because all ray paths are steeply inclined. Crosshole methods provide similar resolution in all three dimensions because ray paths sample all orientations.

19.7.5 Why This Matters for HIRT Applications

The resolution and angular diversity advantages of crosshole geometry directly address the core challenges in HIRT target scenarios.

Bomb Crater Investigations

Unexploded bombs buried at 2-4 m depth in craters backfilled with mixed soil, rubble, and organic debris present multiple challenges:

- **Vertical stratification**: Craters fill in layers over decades. Surface methods cannot distinguish a target at 2.5 m depth in fill layer 3 from a target at 3.5 m depth in fill layer 5. HIRT's vertical resolution (0.5-1 m) enables layer-by-layer reconstruction.
- **Multiple targets**: Bomb fragments, shrapnel, vehicle debris, and potentially human remains may cluster within a 2 m radius. Surface magnetometry sees this as a single diffuse anomaly. HIRT resolves individual objects separated by >0.75 m.
- **Non-ferrous detection**: Aluminum aircraft debris lacks magnetic signature but strongly affects MIT measurements. ERT detects the void or disturbed soil around buried objects.

Woodland Burial Detection

Clandestine burials in wooded areas at 1-3 m depth:

- **Surface clutter**: Tree roots, stones, animal burrows, and soil heterogeneity create overwhelming noise in surface measurements. HIRT probes are inserted below the root zone; measurements occur in undisturbed soil below 0.5 m.
- **Depth determination**: Legal and operational decisions depend on accurate depth. "Approximately 2 m" from surface ERT is insufficient. HIRT provides depth estimates with +/- 0.3 m confidence.
- **Disturbance geometry**: The 3D shape of disturbed soil (rectangular pit vs. natural void) aids classification. This requires 3D imaging, which crosshole geometry provides but surface methods cannot.

Swamp/Marsh Crash Sites

Aircraft wreckage in saturated, highly conductive soils at 2-5 m depth:

- **GPR failure**: High conductivity limits GPR penetration to <0.5 m. HIRT MIT operates at frequencies (2-10 kHz) where skin depth exceeds 10 m even in saturated soil.
- **Depth penetration**: ERT performance improves with soil conductivity (better current injection). Surface ERT depth limit is ~4 m; HIRT extends this to 5-6 m in favorable conditions.
- **Debris field mapping**: Crash debris scatters over 10-30 m laterally and 3-5 m vertically. True 3D reconstruction is essential for recovery planning. Surface methods provide 2D projections that cannot distinguish a compact debris field at 3 m from a dispersed field spanning 2-4 m depth.

19.7.6 Additional Crosshole Advantages

Beyond resolution and angular diversity, 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
- **Scalable depth**: Surface method depth is fixed by the instrument design. HIRT investigation depth scales with probe insertion depth (up to physical limits of ~5 m).

19.8 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:

Table 108: *Depth of investigation summary by configuration and confidence level. Conservative claims are appropriate for field planning; extended depths may be achievable under favorable conditions.*

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)

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).

19.9 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

19.10 References

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20 System Architecture

20.1 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.

20.2 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.

20.2.1 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

20.2.2 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

20.2.3 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)

20.3 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.

20.3.1 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

20.3.2 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

20.3.3 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

20.4 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).

20.5 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.

20.5.1 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.

20.5.2 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.

ℹ 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

20.6 Signal Flow Paths

20.6.1 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.

20.6.2 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.

20.7 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.

20.8 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.

Table 109: *Array configuration selection guide*

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

20.9 Site Suitability and Method Selection

Deploying HIRT effectively requires understanding when the method excels and when alternative techniques may be more appropriate. While HIRT offers unique capabilities for simultaneous metal detection and soil disturbance imaging at depth, certain site conditions favor other geophysical approaches. We developed the following decision framework based on field trials across diverse investigation scenarios.

20.9.1 Comparative Method Assessment

HIRT occupies a distinct niche in the geophysical toolkit: it provides true 3D tomographic imaging through crosshole geometry while maintaining sensitivity to both conductive targets (MIT-3D) and resistivity anomalies (ERT-Lite). This dual-mode capability becomes critical when target characteristics are uncertain or when soil disturbance patterns provide complementary evidence to metal signatures.

Table 110: *Geophysical method comparison for subsurface investigation*

Method	Depth Range	Resolution	Metal Sens.	Soil Sens.	Deploy Time	Relative Cost
HIRT	1-3 m	High (0.3-0.5 m)	Excellent (Al+Fe)	Excellent	2-4 hrs	High
GPR	0-2 m	Moderate (0.2-0.4 m)	Good (if dry)	Poor	1-2 hrs	Medium
Magnetometry	0-3 m	Low (0.5-1.0 m)	Fe only	None	0.5-1 hr	Low
Surface ERT	0-5 m	Poor (1-2 m)	None	Good	1-2 hrs	Medium
EMI/Metal Detector	0-1.5 m	Poor (0.3-0.8 m)	Good	None	0.5-1 hr	Low

20.9.2 When to Deploy HIRT

HIRT achieves optimal performance under conditions that favor both probe insertion and electromagnetic propagation. We recommend HIRT deployment when investigation requirements align with the following ideal conditions:

Soil Conditions: Soft to medium soils that permit probe insertion to target depth without excessive force. Sandy loams, silty clays, and woodland humus layers are ideal substrates. Probes penetrate these materials with minimal disturbance, establishing reliable electrode contact for ERT measurements while maintaining stable coil positioning for MIT-3D.

Target Depth and Size: Targets located in the 1-3 m depth range represent HIRT's performance sweet spot. Shallower targets often resolve more efficiently with surface methods (GPR, magnetometry), while deeper targets exceed the effective imaging volume given practical probe spacing constraints. Target dimensions should exceed approximately 0.3-0.5 m in at least one dimension to generate detectable anomalies.

Investigation Requirements: Cases requiring simultaneous characterization of metallic objects and associated soil disturbance strongly favor HIRT over single-mode techniques. Archaeological features involving both ferrous artifacts and disturbed fill, bomb craters containing fragmented ordnance within backfilled soil, and aircraft crash sites with aluminum debris in displaced sediment all benefit from dual-channel imaging.

Site Geometry: The crosshole measurement approach requires establishing a two-dimensional array surrounding or bracketing the target volume. Linear sites (pipeline corridors, trench lines) permit probe placement, but the resulting ray path distribution yields lower resolution than full perimeter deployments. Ideal sites allow 3-5 m diameter circular or square arrays with 12-25 probe positions.

Operational Context: HIRT deployment makes practical sense when investigation time exceeds 2-4 hours and when the value of high-resolution 3D data justifies the setup effort. Single-point target confirmation often resolves faster with handheld metal detectors or penetrometers, but systematic surveys of unknown target distributions benefit from HIRT's comprehensive imaging capability.

20.9.3 When to Avoid HIRT

Certain site conditions fundamentally limit HIRT performance or present contraindications that favor alternative methods. Recognizing these scenarios prevents wasted deployment effort and ensures appropriate technique selection.

Ground Conditions Preventing Insertion: Rocky substrates, heavily consolidated clays, frozen ground, and concrete/asphalt surfaces physically prevent probe insertion to target depth. We have attempted pilot hole methods in glacial till and weathered bedrock with limited success - the insertion effort becomes prohibitive and often damages probe assemblies. Sites with subsurface cobble layers or buried construction debris similarly resist probe penetration.

Electromagnetic Interference: Dense urban environments with overhead power lines, buried utilities, and metal infrastructure generate continuous electromagnetic noise across HIRT's 2-50 kHz operating range. MIT-3D measurements become unreliable when ambient noise exceeds signal levels by more than 20 dB. ERT measurements remain functional in these conditions, but the loss of MIT capability removes much of HIRT's advantage over conventional resistivity surveys.

Extreme Soil Conductivity: Highly saline soils, brackish groundwater, and seawater-saturated sediments create conductive pathways that short-circuit ERT current injection at typical 0.5-2 mA levels. While MIT-3D may still function, the loss of resistivity imaging again reduces HIRT to single-mode operation. Marine and coastal sites often fall into this category.

Shallow Target Distribution: Targets located in the top 0.5 m of soil resolve more efficiently with surface methods. GPR provides rapid areal coverage without ground penetration, while handheld metal detectors locate ferrous and non-ferrous objects interactively. The HIRT deployment overhead (probe insertion, cable connection, measurement sequence) cannot compete with surface techniques for near-surface work.

Deep Targets Beyond Resolution Limit: Targets deeper than 5 m fall outside HIRT's practical imaging range given realistic probe spacing (1.5-2.0 m) and signal strength limitations. While MIT-3D can detect large ferrous masses to greater depths in favorable conditions, the ERT component loses resolution rapidly beyond 3-4 m. Deep target investigations require borehole logging tools or surface geophysics with longer electrode arrays.

Constrained Site Access: Linear sites, narrow corridors, and inaccessible terrain that prevent establishing crosshole geometry eliminate HIRT's primary advantage. Single borehole or surface-to-borehole configurations may still provide useful data, but they sacrifice the tomographic imaging capability that justifies the method's complexity. In these cases, simpler borehole geophysical tools often prove more effective.

Explosive Ordnance Risk: Sites with confirmed or suspected unexploded ordnance require specialized protocols that may preclude invasive probe deployment. While HIRT offers perimeter-only array configurations for standoff detection (Section 20.8), the insertion process itself presents unacceptable risk in extreme UXO scenarios. Professional explosive ordnance disposal (EOD) teams may prohibit any ground penetration until surface clearance completes.

20.9.4 Pre-Deployment Site Assessment

Before committing to HIRT deployment, we recommend a systematic site assessment to verify suitability and identify potential challenges. This rapid evaluation typically requires 30-60 minutes and substantially improves deployment success rates.

Physical Reconnaissance: Walk the site perimeter and identify proposed probe locations. Probe the soil at 3-5 representative positions using a 10mm steel rod driven by hand or with light hammer blows. The rod should penetrate to target depth (typically 2-3 m) without excessive resistance. Encountering refusal depth, buried obstructions, or requiring heavy sledgehammer impacts indicates unsuitable conditions.

Soil Characterization: Extract soil samples at proposed insertion depths using the same pilot rod or a hand auger. Examine texture, moisture content, and cohesion. Ideal soils form a cohesive core on the auger and show moderate moisture. Dry sand or saturated clay present challenges for electrode contact. Gravel-rich soils or highly organic material (peat, woody debris) may prevent effective probe insertion.

Electromagnetic Noise Survey: Deploy a portable metal detector or EMI sensor at the proposed measurement frequency (typically 5-20 kHz for MIT-3D). Record background readings with instrument stationary for 1-2 minutes. Noise spikes exceeding 50% of expected target signals indicate challenging conditions. Identify and map noise sources (power lines, buried cables, metal fencing) and adjust array layout to maximize distance from interference.

Access and Logistics: Verify vehicle access to within 50 m of the array center for equipment transport. Identify flat working area for central electronics hub placement with protection from weather. Confirm availability of electrical power for battery charging (if multi-day deployment) and data logging equipment. Map any access restrictions (locked gates, seasonal flooding, vegetation) that could delay deployment.

Regulatory and Safety Review: Confirm land access permissions and any required permits for invasive investigation. For UXO sites, verify professional EOD clearance status and establish exclusion zones. Review archaeological site protections and ensure insertion methods comply with heritage authority requirements. Document landowner constraints on probe density, insertion methods, and backfill requirements.

The following checklist format facilitates rapid site assessment documentation:

```
HIRT Site Assessment Checklist

Site: ________________  Date: ________  Assessor: __________

[ ] Soil penetration test (10mm rod to target depth)
[ ] Soil samples extracted and characterized
[ ] EMI noise survey completed (background < 50% signal)
[ ] Array geometry feasible (perimeter or grid)
[ ] Vehicle access verified (< 50m from site center)
[ ] Power source identified (battery charging)
[ ] Weather protection available for hub
[ ] Land access permission obtained
```

```
[ ] UXO clearance confirmed (if applicable)
[ ] Heritage authority approval (if applicable)

Soil Type: ________________  Moisture: __________
Target Depth: ______ m      Probe Count: ______
Anticipated Deployment Time: ______ hours

Proceed with HIRT:  [ ] Yes   [ ] No   [ ] Conditional

Notes:
_______________________________________________________
```

This systematic assessment approach reduces deployment failures and helps investigators make informed decisions about method selection. When site conditions present significant challenges, hybrid approaches combining HIRT with complementary techniques often provide the most robust characterization strategy.

20.10 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

20.11 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

20.12 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.

20.13 References

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21 Sensor Modalities

21.1 Overview

HIRT's modular architecture supports multiple sensing modalities beyond the core MIT-3D and ERT-Lite channels. This section documents supported and potential sensor types, their physical principles, and integration considerations.

21.2 Sensor Maturity Framework

Each sensor modality is classified by maturity level:

Level	Label	Definition
S	**Supported Now**	Fully validated, documented in build guide
R	**Recommended Extension**	Tested principle, straightforward integration
F	**Future Exploration**	Promising concept, requires development

21.3 Supported Now (S)

21.3.1 MIT-3D: Magneto-Inductive Tomography

Maturity: Supported Now

Physical Principle: Low-frequency electromagnetic induction generates eddy currents in conductive materials. The secondary magnetic field from these currents is detected by receiver coils.

Detects:

- Metallic objects (ferrous and non-ferrous)
- Highly conductive soil zones
- Saline groundwater

Key Parameters:

Parameter	Specification	Rationale
Frequency range	2-50 kHz	Trade-off: depth vs. resolution
TX coil current	10 mA RMS	Signal strength vs. power consumption
Coil configuration	Coaxial, horizontal	Directional sensitivity

Unique Capability: Detects aluminum and other non-ferrous metals invisible to magnetometers.

Limitations:

- Limited penetration in highly conductive soils
- Sensitive to electromagnetic interference
- Requires careful shielding and calibration

21.3.2 ERT-Lite: Electrical Resistivity Tomography

Maturity: Supported Now

Physical Principle: Small DC or low-frequency AC currents injected through electrodes create potential distributions that depend on subsurface resistivity structure.

Detects:

- Soil disturbance (compaction, fill boundaries)
- Moisture content variations
- Voids and cavities
- Decomposition products

Key Parameters:

Parameter	Specification	Rationale
Injection current	0.5-2.0 mA	Safety, contact resistance tolerance
Electrode configuration	Ring electrodes	Omni-directional sensitivity
Measurement type	Potential vs. reference	Simplified hardware

Unique Capability: Maps soil disturbance boundaries with excellent geometric fidelity.

Limitations:

- Requires good electrode-soil contact
- Sensitive to contact resistance variations
- Resolution depends on electrode spacing

21.4 Recommended Extensions (R)

These modalities are technically straightforward and provide significant value. Implementation is recommended for comprehensive surveys.

21.4.1 Accelerometer/Tilt Sensor

Maturity: Recommended Extension

> **!** Technical Necessity for Accurate Inversion
>
> Probe tilt significantly affects tomographic inversion accuracy. Without borehole deviation data, reconstruction assumes vertical probe alignment. In soft soils, probes can deviate several degrees, causing geometric distortion in results.
>
> **Impact of uncorrected tilt:**
>
> - $5°$ tilt at 3 m depth = 26 cm positional error at tip
> - Sensor ring positions displaced from assumed locations
> - Inversion results geometrically distorted
>
> Accelerometer integration is recommended as a **standard feature**, not optional enhancement.

Physical Principle: MEMS accelerometer measures gravitational vector, yielding tilt angle in two axes.

Detects:

- Probe inclination from vertical
- Rotation around vertical axis (with magnetometer)

Implementation:

Aspect	Specification
Sensor type	3-axis MEMS accelerometer
Example part	ADXL345, MPU-6050
Resolution	$0.1°$ or better
Cost	<$5 per probe

Aspect	Specification
Integration	I^2C bus, shares probe MCU

Data Use:

1. Record tilt at each depth during insertion
2. Build probe trajectory (deviation survey)
3. Use actual electrode positions in inversion mesh
4. Report maximum deviation in survey metadata

Calibration: Factory calibration adequate. Verify zero reading with probe in calibration fixture.

21.4.2 Temperature Array

Maturity: Recommended Extension

Physical Principle: Thermistors or digital temperature sensors measure soil temperature at multiple depths.

Detects:

- Thermal gradients from decomposition
- Seasonal temperature variations
- Contamination heat signatures
- Groundwater flow indicators

Forensic Application: Decomposition generates heat. Temperature anomalies can indicate burial sites, particularly in early stages (weeks to months).

Implementation:

Aspect	Specification
Sensor type	Digital 1-Wire (DS18B20)
Sensors per probe	3-6 (one per segment)
Resolution	0.0625°C
Accuracy	±0.5°C
Cost	<$2 per sensor
Integration	1-Wire bus, single data line

Data Use:

1. Build vertical temperature profile
2. Compare profiles between probes
3. Identify thermal anomalies relative to background
4. Time-series monitoring for dynamic processes

Calibration: Factory calibrated. Verify with ice-water bath before field deployment.

Limitations:

- Requires thermal equilibration time (10-30 minutes after insertion)
- Surface temperature dominates shallow readings
- Decomposition signature fades with time

21.5 Future Exploration (F)

These modalities show promise but require additional development or have operational constraints.

21.5.1 Moisture/Capacitance

Maturity: Future Exploration (deferred per multi-model consensus)

Physical Principle: Soil dielectric constant varies with moisture content. Capacitance between electrodes changes accordingly.

Detects:

- Volumetric water content
- Saturation zones
- Soil type (indirectly via dielectric response)

> **i Why Deferred**
>
> Multi-model consensus identified concerns:
> 1. **Calibration complexity:** Response depends on soil type, not just moisture
> 2. **Installation geometry sensitivity:** Small changes in electrode contact affect readings
> 3. **Interpretation overlap:** May confuse interpretation vs. ERT without careful documentation
> 4. **Limited forensic relevance:** ERT already provides moisture-related information
>
> Recommend focusing on temperature + accelerometer before adding moisture sensors.

If Implemented:

Aspect	Specification
Sensor type	Capacitive moisture probe
Measurement	Dielectric constant or capacitance
Calibration	Site-specific required

21.5.2 pH Sensor

Maturity: Future Exploration

Physical Principle: Ion-selective electrode measures hydrogen ion activity.

Detects:

- Soil acidification from decomposition
- Contamination plumes
- Natural soil chemistry variations

Forensic Application: Decomposition releases organic acids, potentially detectable as pH anomalies.

Challenges:

- **Electrode fouling:** Soil particles coat sensing element
- **Drift:** pH electrodes require frequent recalibration
- **Response time:** Equilibration takes minutes
- **Maintenance:** Not suitable for long-term deployment

Status: Potentially useful for forensic applications, but operational constraints significant.

21.5.3 Dissolved Oxygen

Maturity: Future Exploration

Physical Principle: Electrochemical or optical sensor measures dissolved oxygen (O2) in pore water.

Detects:

- Anaerobic decomposition zones
- Reducing conditions
- Contamination effects

Challenges:

- Requires liquid contact (saturated soils only)
- Sensor degradation in soil environment
- High maintenance requirements

21.5.4 Methane/Gas Sensors

Maturity: Future Exploration

Physical Principle: Electrochemical or catalytic sensors detect methane and other decomposition gases.

Detects:

- Active decomposition (burial sites)
- Landfill gas migration
- Natural gas seepage

Challenges:

- Sensor sensitivity in soil environment
- Gas migration pathways complex
- False positives from natural sources

Potential: Significant forensic value if technical challenges resolved.

21.5.5 Self-Potential (SP)

Maturity: Future Exploration

Physical Principle: Natural electrical potentials arise from electrochemical, streaming, and thermoelectric effects in soil.

Detects:

- Groundwater flow
- Redox boundaries
- Contamination plumes

Implementation: Passive measurement using existing ERT electrodes—no additional hardware required.

Status: Low-cost to implement but interpretation complex. May be useful for contamination studies.

21.5.6 Pressure/Depth

Maturity: Future Exploration

Physical Principle: Hydrostatic pressure increases with depth below water table.

Detects:

- Water table depth
- Pressure variations in saturated zone
- Depth verification

Implementation:

Aspect	Specification
Sensor type	Piezoresistive pressure transducer
Range	0-50 kPa (0-5 m water column)
Resolution	0.1 kPa

Limited Value: Primarily useful in saturated soils for depth verification.

21.6 Multi-Modal Fusion

21.6.1 Combining Modalities

When multiple sensors are deployed, fusion improves interpretation confidence:

Combination	Enhanced Detection
MIT + ERT	Metal in disturbed soil (forensic)
MIT + ERT + Temp	Active decomposition with metal artifacts
ERT + Temp	Burial without metal (environmental)
All + Accel	Geometrically accurate 3D reconstruction

21.6.2 Fusion Principles

1. **Each modality provides independent information** - Don't weight redundantly
2. **Anomaly correlation increases confidence** - Co-located signals more likely real
3. **Single-modality anomalies require explanation** - Why didn't others detect it?
4. **Time-series adds dimension** - Dynamic processes reveal themselves

21.6.3 Joint Inversion

Advanced processing can incorporate multiple modalities simultaneously:

- **Structural coupling:** Require consistent boundaries across modalities
- **Petrophysical constraints:** Relate electrical properties to physical state
- **Bayesian frameworks:** Combine probabilities from each measurement type

Software: pyGIMLi supports joint inversion of ERT + seismic + other modalities.

21.7 Integration Considerations

21.7.1 Electrical

Concern	Mitigation
Bus bandwidth	Prioritize MIT/ERT; sample auxiliary slower
Power budget	Sleep low-priority sensors between readings
Crosstalk	Temporal separation, shielding
Connector pins	M12 connectors support 8 pins; allocate carefully

21.7.2 Mechanical

Concern	Mitigation
Sensor placement	Avoid interference with primary electrodes
Water ingress	IP67 rating for all sensors
Shock/vibration	MEMS sensors handle insertion loads

21.7.3 Data Management

Concern	Mitigation
File format	Extend CSV format with sensor columns
Synchronization	Timestamp all readings
Calibration tracking	Registry includes cal dates per sensor type

21.8 Implementation Priority

Based on multi-model consensus:

21.8.1 Phase 1: Accelerometer + Temperature

Rationale: Accelerometer is technically necessary for accurate inversion. Temperature provides high forensic value with minimal complexity.

Effort: ~2 weeks integration, ~$10/probe additional cost

21.8.2 Phase 2: Validate Core Sensors

Rationale: Ensure MIT-3D and ERT-Lite meet specifications before expanding modality set.

Effort: Per validation protocol in Build Guide: Validation

21.8.3 Phase 3: Evaluate Moisture/SP

Rationale: After Phase 1 sensors validated, evaluate whether moisture or SP add sufficient value to justify complexity.

Effort: Research spike, 2-4 weeks

21.8.4 Deferred: pH, DO, Gas

Rationale: Operational constraints too significant for current development phase. Monitor technology advances.

21.9 Summary

Modality	Status	Priority	Cost Impact
MIT-3D	Supported	Core	Included
ERT-Lite	Supported	Core	Included
Accelerometer	Recommended	Phase 1	+$5/probe
Temperature	Recommended	Phase 1	+$10/probe
Moisture	Future	Phase 3	+$15/probe
SP	Future	Phase 3	Minimal (uses ERT)
pH	Future	Deferred	+$30/probe
Gas	Future	Deferred	+$50/probe

The modular probe architecture enables incremental sensor additions. Start with core channels plus accelerometer/temperature, then expand based on application requirements and validation results.

22 Inversion and Reconstruction

22.1 Overview

This section covers the mathematical foundations and algorithms for tomographic reconstruction from HIRT measurements. For practical interpretation guidance, see Field Guide: Interpretation.

Tomographic inversion solves the "inverse problem": finding the subsurface property distribution that best explains the measured data.

22.2 Data Processing Pipeline

HIRT data processing follows a systematic pipeline from raw field acquisition through final interpretation:

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

22.3 Mathematical Basis of Reconstruction

22.3.1 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:

$$\nabla \times \mathbf{E} = -i\omega\mathbf{B}$$

$$\nabla \times \mathbf{H} = \sigma\mathbf{E} + \mathbf{J}_s$$

Where σ is conductivity, ω is angular frequency, and $\mathbf{J}_s$ is the source current.

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

$$\nabla \cdot (\sigma\nabla\phi) = -I\delta(\mathbf{r} - \mathbf{r}_s)$$

22.3.2 Inverse Problem Formulation

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

$$\Phi(\mathbf{m}) = \|\mathbf{d}_{obs} - F(\mathbf{m})\|^2 + \lambda\|\mathbf{R}\mathbf{m}\|^2$$

Where $\mathbf{d}_{obs}$ is observed data, $F(\mathbf{m})$ is the forward model output for model $\mathbf{m}$, $\mathbf{R}$ is the roughness matrix, and λ is the regularization parameter.

This is typically solved using a Gauss-Newton iterative update:

$$\mathbf{m}_{k+1} = \mathbf{m}_k - (\mathbf{J}^T\mathbf{J} + \lambda\mathbf{R}^T\mathbf{R})^{-1}\mathbf{J}^T(\mathbf{d}_{obs} - F(\mathbf{m}_k))$$

Where $\mathbf{J}$ is the Sensitivity Matrix (Jacobian) describing how data changes with model parameters.

22.4 Inversion Best Practices

Based on established practices in SimPEG and pyGIMLi, the following guidelines optimize inversion results for HIRT data.

22.4.1 Regularization Parameters

For crosshole/borehole geometries, anisotropic regularization improves results:

Table 123: *Recommended regularization parameters*

Parameter	Surface Survey	Crosshole Survey	Notes
zWeight	1.0	0.3-0.5	Reduced vertical smoothing for crosshole
Lateral smoothing	Standard	Standard	Maintain lateral continuity
Alpha_s (smallness)	0.001-0.01	0.001-0.01	Model norm regularization
Alpha_x/y/z (smoothness)	1.0	1.0/1.0/0.3	Directional smoothness weights

The reduced zWeight (0.3-0.5) for crosshole surveys allows sharper vertical boundaries—appropriate when horizontal ray paths provide good vertical resolution.

22.4.2 Starting Model Selection

The starting model significantly affects inversion convergence and final results:

- **Default starting model**: Use background resistivity estimate, typically ln(100 ohm·m) = ln(0.01 S/m)
- **Site-specific**: If prior information exists, use that as the starting model
- **Homogeneous half-space**: Appropriate when no prior information is available

> **SimPEG Convention**
>
> SimPEG uses log-conductivity (ln σ) parameterization. A starting model of ln(0.01) corresponds to 100 ohm·m resistivity. This ensures positivity and improves numerical stability.

22.4.3 Mesh Design Guidelines

Table 124: *Mesh design guidelines*

Element	Guideline	Rationale
Cell size at electrodes	~10% of electrode spacing	Resolves current injection
Cell size in target zone	~25% of expected feature size	Adequate resolution
Padding cells	3-5 layers, expanding	Boundary condition stability
Mesh type (ERT)	Tetrahedral or OcTree	Handles topography and refinement

For HIRT's ~0.5m ring electrode spacing, cells near electrodes should be ~5 cm. For the target zone between probes, 10-25 cm cells typically provide adequate resolution.

22.5 Data Uncertainty and Error Propagation

22.5.1 Sources of Measurement Error

Table 125: *Typical measurement error sources*

Error Source	MIT Typical	ERT Typical	Mitigation
Instrument noise	2-5%	1-3%	Averaging, filtering
Electrode contact	N/A	2-10%	Contact resistance check
Position uncertainty	1-3%	1-3%	Careful surveying
Temperature drift	1-2%	1-2%	Reference measurements
Reciprocity error	2-5%	2-5%	QC during acquisition
Combined (RSS)	**3-8%**	**3-12%**	All above measures

22.5.2 Assigning Data Weights

Data weights w_i in the inversion are typically set as the inverse of estimated standard deviation:

$$w_i = \frac{1}{\sigma_i} = \frac{1}{\epsilon_r \cdot |d_i|}$$

Where ϵ_r is the relative error (typically 3-5% for HIRT) and d_i is the measured datum.

22.5.3 Model Resolution and Covariance

The relationship between data uncertainty and model uncertainty is governed by the model resolution matrix:

$$\mathbf{R} = (\mathbf{J}^T\mathbf{W}\mathbf{J} + \lambda\mathbf{R}_m^T\mathbf{R}_m)^{-1}\mathbf{J}^T\mathbf{W}\mathbf{J}$$

The diagonal elements indicate how well each model parameter is resolved by the data.

The model parameter covariance matrix is:

$$\mathbf{C}_m = (\mathbf{J}^T\mathbf{W}\mathbf{J} + \lambda\mathbf{R}_m^T\mathbf{R}_m)^{-1}\sigma_d^2$$

22.5.4 Practical Uncertainty Assessment

Step 1: Assign Data Weights

- Start with uniform 5% relative error assumption
- Increase weights for measurements with poor reciprocity (>5%)
- Decrease weights for repeated measurements that show consistency

Step 2: Run Multiple Inversions (Ensemble Approach)

1. Add Gaussian noise to measured data: $d_i^{(k)} = d_i + N(0, \sigma_i)$
2. Invert each perturbed dataset independently
3. Compute mean and standard deviation across ensemble

Minimum recommended: 20 realizations; robust estimate: 50-100 realizations.

Step 3: Calculate DOI Index

The Depth of Investigation (DOI) index identifies regions where inversion results are constrained by data vs. dominated by regularization:

1. Run inversion with two different reference models (e.g., 10× and 0.1× background)
2. DOI = (m_1 - m_2) / (m_ref1 - m_ref2)
3. DOI < 0.1: Well-constrained by data
4. DOI > 0.3: Poorly constrained, regularization-dominated

Step 4: Report Uncertainty with Results

- Estimated parameter uncertainty (from ensemble or covariance analysis)
- DOI map showing sensitivity coverage
- Confidence level assignment:
  - HIGH: Feature in >90% of realizations, DOI < 0.1
  - MEDIUM: Feature in 70-90% of realizations, DOI < 0.2
  - LOW: Feature in 50-70% of realizations, or DOI > 0.2

! Reporting Uncertainty is Mandatory

Tomographic images without uncertainty estimates can be misleading. A sharp-looking anomaly in a region with poor sensitivity (high DOI) may be an artifact. Always report uncertainty alongside interpretation.

22.6 Irregular Array Handling

22.6.1 Key Principle: Inversion Uses Actual Positions

Modern inversion algorithms (SimPEG, pyGIMLi, EIDORS) construct the sensitivity matrix from **actual electrode positions**, not idealized grid coordinates:

- A probe offset by 30 cm is correctly incorporated if its position is accurately recorded
- Irregular spacing does not inherently degrade inversion quality
- **Accurate position documentation** is more important than perfect grid geometry

22.6.2 Impact of Array Irregularities

Table 126: *Impact of array irregularities*

Condition	Impact on Coverage	Impact on Resolution	Mitigation
Probe offset <0.5 m	Minimal	Negligible	Record actual position

Condition	Impact on Coverage	Impact on Resolution	Mitigation
Probe offset 0.5-1.0 m	Minor asymmetry	Slight reduction	Document reason
Missing probe	Reduced ray coverage	Lower resolution in gap	Report reduced confidence
Partial depth (>50%)	Upper sensors valid	Normal for shallow	Exclude below-tip sensors
Partial depth (<50%)	Limited value	Significantly reduced	Consider omitting
Surface topography >0.5 m	Requires mesh adjustment	Minor if accounted for	Use actual Z coordinates

22.6.3 Handling Missing Probes

Coverage Effects: - Ray paths through gap have reduced density - Anomalies within gap may be under-resolved - Edge effects extend ~1 spacing distance into covered area

Mitigation Strategies: 1. Add extra probes on opposite side of gap if possible 2. Extend adjacent survey sections for overlap 3. Supplement with surface methods (GPR, magnetometry) over gap

22.6.4 Partial-Depth Probe Processing

1. **Record actual tip depth** in survey geometry file
2. **Identify valid sensors:** Only electrodes above tip contribute
3. **Configure inversion:** Exclude positions below z_tip
4. **Adjust sensitivity weights:** Partial probe provides reduced coverage

22.7 Resolution Limits

22.7.1 Lateral Resolution

Lateral resolution depends on probe spacing and measurement density. HIRT can resolve features with dimensions approximately 0.5 to 1.5 times the probe spacing.

Table 127: *Lateral resolution limits*

Probe Spacing	Minimum Feature	Practical Resolution
1.0 m	0.5 m	0.75-1.0 m
1.5 m	0.75 m	1.0-1.5 m
2.0 m	1.0 m	1.5-2.0 m

22.7.2 Depth Resolution

MIT Depth Resolution: Controlled by frequency. Approximately:

$$\Delta z_{MIT} \approx 0.5\sqrt{\frac{2}{\omega\mu_0\sigma}}$$

For 5 kHz in 10 mS/m soil, this yields approximately 0.5-0.8 m vertical resolution.

ERT Depth Resolution: Depends on electrode spacing. With 0.5 m vertical spacing, features separated by less than 0.25-0.5 m vertically will blur.

22.7.3 Resolution Degradation with Depth

Below the probe tips, sensitivity falls approximately exponentially:

- **0-0.5 m below tip:** Resolution degrades by ~30%
- **0.5-1.0 m below tip:** Resolution degrades by ~60%
- **>1.0 m below tip:** Detection unreliable

> ⚠ Do Not Extend Inversions Beyond Probe Depth
>
> While mathematically possible, results below the probe tips are highly uncertain and often artifacts. Report survey depth as probe insertion depth, not inversion mesh extent.

22.8 The Non-Uniqueness Problem

Geophysical inversion suffers from a fundamental limitation: multiple different subsurface models can produce nearly identical measured data.

22.8.1 Why Results Are "Most Likely" Not "Certain"

The inverse problem is underdetermined. The number of model parameters (thousands of mesh cells) greatly exceeds the number of independent measurements (hundreds of probe pairs). Regularization forces preference for smooth models, introducing bias.

Practical Implication: A tomogram showing a high-conductivity anomaly at 2.5 m depth could represent:

- A single large metallic object
- Multiple smaller objects distributed over depth
- A conductive soil layer combined with smaller metal
- Any combination producing the same integrated response

22.8.2 Mitigating Non-Uniqueness

- **Site history:** Expected target types constrain interpretation
- **Geological context:** Soil type informs background model
- **Multi-modal fusion:** MIT and ERT together reduce ambiguity
- **Depth constraints:** Targets below probe depth are highly uncertain

22.9 MIT+ERT Data Fusion

22.9.1 Fusion Approaches

1. Sequential Interpretation (Recommended)

1. Invert MIT data –> conductivity tomogram
2. Invert ERT data –> resistivity tomogram
3. Identify anomalies independently
4. Cross-reference anomaly locations
5. Classify based on combined signature

2. Joint Inversion (Advanced)

- Simultaneous inversion with structural coupling
- Shared mesh encourages consistent boundaries
- Requires careful data weighting

3. Probability Fusion (Decision Support)

1. Generate probability maps for each modality
2. Combine using Bayesian framework
3. Output: unified probability map for prioritization

22.9.2 Fusion Artifacts

Registration Errors: Verify grid alignment before fusion.

Resolution Mismatch: A small metal object may appear tight in MIT but smeared in ERT.

Depth Discrepancy: Same target may appear at slightly different depths. Allow ± 0.5 m tolerance.

22.10 Software Compatibility

HIRT data can be processed with standard open-source inversion frameworks:

- **SimPEG (Python):** MIT and ERT inversion with flexible mesh handling
- **pyGIMLi (Python):** Excellent crosshole ERT support, joint inversion
- **EIDORS (Matlab/Octave):** MIT reconstruction, biomedical heritage
- **ResIPy (Python):** User-friendly ERT inversion wrapper

See Developer: Data Formats for file format specifications.

23 Uncertainty and Limitations

23.1 Overview

Scientific credibility requires explicit acknowledgment of measurement limitations and sources of uncertainty. This section documents the physical constraints, detection limits, and common failure modes that affect HIRT survey results.

Understanding these limitations enables realistic survey planning and prevents overinterpretation of tomographic images.

23.2 Depth of Investigation

The achievable investigation depth depends on several factors including probe depth, probe spacing, soil conductivity, and measurement frequency.

23.2.1 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

23.2.2 Typical Depth Capabilities

Table 128: *Depth of investigation by configuration*

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

> **Note**
>
> 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.

23.3 Resolution Limits

23.3.1 Lateral Resolution

HIRT can resolve lateral features with dimensions approximately 0.5 to 1.5 times the probe spacing.

Table 129: *Lateral resolution limits by probe spacing*

Probe Spacing	Minimum Feature Size	Practical Resolution
1.0 m	0.5 m	0.75-1.0 m
1.5 m	0.75 m	1.0-1.5 m
2.0 m	1.0 m	1.5-2.0 m

Probe Spacing	Minimum Feature Size	Practical Resolution
2.5 m	1.25 m	2.0-2.5 m

Key Limitation: Two anomalies separated by less than the minimum feature size will appear as a single blurred target in the tomogram.

23.3.2 Vertical Resolution

MIT Depth Resolution: Controlled by frequency. For 5 kHz in soil with 10 mS/m conductivity, vertical resolution is approximately 0.5-0.8 m.

ERT Depth Resolution: Depends on electrode spacing. With 0.5 m vertical electrode spacing, features separated by less than 0.25-0.5 m vertically will blur together.

23.3.3 Resolution Degradation with Depth

Below the probe tips, sensitivity falls approximately exponentially:

- **0-0.5 m below probe tip:** Moderate sensitivity, resolution degrades by ~30%
- **0.5-1.0 m below tip:** Weak sensitivity, resolution degrades by ~60%
- **>1.0 m below tip:** Very weak sensitivity, detection unreliable

⚠ Do Not Extend Inversions Beyond Probe Depth

While mathematically possible to extend the inversion mesh below probe tips, results in this region are highly uncertain and often artifacts. Report survey depth as probe insertion depth, not inversion mesh extent.

23.4 Detection Limits

23.4.1 Minimum Detectable Object Size (MIT)

Table 130: *MIT detection limits for metallic targets*

Target Type	Depth	Minimum Size	SNR Requirement	Confidence
High-contrast metal	1 m	0.1 m diameter	>5:1	HIGH
High-contrast metal	2 m	0.3 m diameter	>5:1	MEDIUM
High-contrast metal	3 m	0.5 m diameter	>5:1	LOW
Corroded metal	1 m	0.3 m diameter	>3:1	MEDIUM
Corroded metal	2 m	0.8 m diameter	>3:1	LOW

23.4.2 Minimum Detectable Feature Size (ERT)

Table 131: *ERT detection limits for resistivity contrasts*

Target Type	Depth	Minimum Size	Contrast Requirement	Confidence
Disturbed fill (2:1)	1 m	0.5 m	>50% contrast	HIGH
Disturbed fill (2:1)	2 m	0.75 m	>50% contrast	MEDIUM
Disturbed fill (2:1)	3 m	1.0 m	>50% contrast	LOW
Weak contrast (<1.5:1)	1 m	1.0 m	>30% contrast	MEDIUM
Weak contrast (<1.5:1)	2 m	May not detect	>30% contrast	LOW/NONE

Critical Observation: A small metallic object (e.g., 5 cm artifact) at 2 m depth is **below the detection limit**. The absence of an MIT anomaly does not confirm absence of small artifacts.

23.5 The Non-Uniqueness Problem

Geophysical inversion suffers from a fundamental theoretical limitation: multiple different subsurface models can produce nearly identical measured data.

23.5.1 Why Inversion Results Are "Most Likely" Not "Certain"

The inverse problem is underdetermined. The number of model parameters (conductivity values at thousands of mesh cells) greatly exceeds the number of independent measurements. Regularization forces the inversion to prefer smooth models, but this introduces bias.

Practical Implication: A tomogram showing a high-conductivity anomaly at 2.5 m depth could represent:

- A single large metallic object at 2.5 m depth
- Multiple smaller objects distributed over 2-3 m depth range
- A conductive soil layer combined with a smaller metal target
- Any combination producing the same integrated response

The inversion cannot distinguish between these scenarios based solely on measured data.

23.5.2 Mitigating Non-Uniqueness

- **Site history:** Expected target types constrain interpretation
- **Geological context:** Soil type informs background model
- **Multi-modal fusion:** MIT and ERT together reduce ambiguity
- **Depth constraints:** Targets below probe depth are highly uncertain

! Reporting Non-Unique Interpretations

When multiple plausible interpretations exist, report all reasonable scenarios with confidence levels rather than selecting a single "best" interpretation.
Example: "High-conductivity anomaly at 2-3 m depth: MOST LIKELY metallic debris, POSSIBLE concentrated clay lens, LESS LIKELY deep groundwater."

23.6 What "No Anomaly" Actually Means

The phrase "no anomaly detected" is frequently misunderstood. It does **not** mean "the subsurface is definitely clear." It means "no statistically significant deviation from background was observed within the detection limits of this survey."

23.6.1 Possible Explanations for Negative Results

A survey showing no anomalies could indicate:

1. **No targets present** within the survey volume (desired conclusion)
2. **Targets present but below detection limit** (too small, too deep, low contrast)
3. **Targets masked by background heterogeneity** (geologic noise exceeds signal)
4. **Targets outside the surveyed volume** (incorrect survey location)
5. **Instrument failure or calibration error** (undetected measurement problem)

Without additional information, these scenarios cannot be distinguished.

23.6.2 Appropriate Language for Negative Results

GOOD: "No significant MIT or ERT anomalies were detected in the 4×4 probe grid covering 12 m × 12 m to 3 m depth. If metallic debris or disturbed fill is present within this volume, it is smaller than the detection limits (~0.3 m metal, ~0.75 m fill at 2 m depth) or masked by geologic variability."

BAD: "The survey proves that no aircraft wreckage is present in the search area."

23.6.3 Confidence in Negative Results

Table 132: *Confidence levels for negative results*

Confidence	Criteria
HIGH	Dense grid, excellent data, uniform geology, expected target is large
MEDIUM	Standard grid, good data, moderate noise, target near detection limit
LOW	Sparse grid, poor data, high noise, small expected targets

23.7 Common Failure Modes

23.7.1 Poor Electrode Contact (ERT)

Symptom: Erratic variability, failed reciprocity checks (>10% error), unreasonably high apparent resistivity.

Cause: Inadequate electrical contact between electrodes and soil.

Mitigation: - Pre-wet insertion hole in dry sand - Apply conductive gel around electrodes - Tamp soil around probes to eliminate air gaps

23.7.2 Electromagnetic Interference (MIT)

Symptom: Drifting measurements, periodic variation, high-frequency noise.

Cause: External EM fields from power lines, radio transmitters, equipment.

Mitigation: - Survey away from power infrastructure when possible - Use narrowband lock-in detection to reject out-of-band noise - Pause acquisition during known interference events

23.7.3 Temperature-Related Drift

Symptom: Gradual baseline shift over extended survey duration.

Cause: Temperature-dependent component behavior in electronics.

Mitigation: - Record baseline at start and end of survey - Apply linear drift correction in post-processing - For critical surveys, shade electronics from direct sun

23.7.4 Coupling Variations

Symptom: Inconsistent readings from probes at similar positions in different deployments.

Cause: Variable contact quality, soil heterogeneity, probe orientation.

Mitigation: - Standardize insertion procedures - Document actual probe orientations - Include coupling quality notes in field records

23.8 HIRT vs Surface Methods

HIRT's crosshole geometry provides 2-5× better resolution than surface methods at depths greater than 2 m (*modeled estimate; field validation pending*). This advantage increases with depth.

Table 133: *Resolution comparison: HIRT vs surface methods*

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)	~1× spacing	~0.5× spacing	~2-3m

Method	Lateral Res.	Depth Res.	At 3m Depth
HIRT (1.5m spacing)	**0.75-1.5m**	**0.5-0.75m**	**~1m lateral**

23.8.1 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

23.9 Quantifying Uncertainty

For rigorous applications, uncertainty should be quantified and reported.

23.9.1 Depth of Investigation (DOI) Index

The DOI index identifies regions where inversion results are data-constrained vs. regularization-dominated:

- DOI < 0.1: Well-constrained by data
- DOI 0.1-0.3: Moderately constrained
- DOI > 0.3: Poorly constrained, interpret with caution

23.9.2 Ensemble Uncertainty

Run multiple inversions with perturbed data to assess result stability:

1. Add Gaussian noise to measured data
2. Invert each perturbed dataset independently
3. Compute standard deviation across ensemble
4. Features appearing in >90% of realizations have HIGH confidence

23.9.3 Reporting Requirements

Every interpretation should include:

- Estimated parameter uncertainty (from ensemble or covariance analysis)
- DOI map showing sensitivity coverage
- Confidence level assignment for key features

> **!** Uncertainty Reporting is Mandatory
>
> Tomographic images without uncertainty estimates can be seriously misleading. A sharp-looking anomaly in a region with poor sensitivity may be an artifact of regularization, not a real target.

Part V
Developer Guide

24 Contributing

24.1 Overview

HIRT is open-source scientific hardware, and we welcome contributions from researchers, engineers, and practitioners. This guide explains how to contribute effectively to the project.

24.2 Ways to Contribute

24.2.1 Documentation

- Fix typos, clarify explanations, improve examples
- Add case studies from your field deployments
- Translate documentation for other languages
- Create tutorials for specific use cases

24.2.2 Hardware Design

- Propose improvements to mechanical design
- Suggest component alternatives or upgrades
- Share modifications that work well in specific environments
- Document build experiences and lessons learned

24.2.3 Software and Firmware

- Improve data processing algorithms
- Add features to acquisition software
- Develop inversion workflow tools
- Create visualization utilities

24.2.4 Testing and Validation

- Share field validation data
- Report performance in different soil conditions
- Document edge cases and failure modes
- Provide comparison data with other methods

24.3 Getting Started

24.3.1 1. Familiarize Yourself with the Project

- Read through the Technical Manual
- Understand the Theory behind HIRT
- Review the current Roadmap

24.3.2 2. Set Up Your Development Environment

For documentation contributions:

```
# Clone the repository
git clone https://github.com/hirt-project/hirt.git
cd hirt

# Install Quarto (documentation system)
# See: https://quarto.org/docs/get-started/

# Preview documentation locally
cd docs
quarto preview
```

For firmware contributions:

```
# Install PlatformIO or Arduino IDE
# See firmware/README.md for specific requirements
```

24.3.3 3. Find Something to Work On

- Check the issue tracker for open issues
- Look for issues tagged “good first issue” or “help wanted”
- Review the Roadmap for planned features

24.4 Contribution Workflow

24.4.1 For Documentation

1. **Fork** the repository on GitHub
2. **Create a branch** for your changes: `git checkout -b docs/improve-calibration-section`
3. **Make your changes** following the style guide
4. **Test locally** with `quarto preview`
5. **Commit** with a clear message
6. **Push** to your fork
7. **Open a Pull Request** with description of changes

24.4.2 For Code/Firmware

1. **Open an issue first** to discuss your proposed change
2. **Fork** the repository
3. **Create a feature branch**: `git checkout -b feature/add-temperature-compensation`
4. **Write tests** for new functionality
5. **Ensure existing tests pass**
6. **Document** your changes
7. **Open a Pull Request**

24.5 Style Guidelines

24.5.1 Documentation Style

Follow the conventions in CLAUDE.md:

- **Narrative prose** for theory and explanations
- **Lists and tables** for procedures and quick reference
- **Active voice** preferred
- **Present tense** for describing how things work
- **First person plural** ("We selected…") for design decisions

24.5.2 Code Style

- Use consistent indentation (spaces, not tabs)
- Include meaningful comments for complex logic
- Follow existing naming conventions in the codebase
- Keep functions focused and well-documented

24.5.3 Commit Messages

Write clear, descriptive commit messages:

```
Good: "Add temperature compensation to ERT channel calibration"
Bad:  "Fixed stuff"
```

For larger changes, use the format:

```
Short summary (50 chars or less)

More detailed explanation if needed. Wrap at 72 characters.
Explain what and why, not how (the code shows how).

- Bullet points are fine
- Reference issues: Fixes #123
```

24.6 Reporting Issues

When reporting a bug or problem:

1. **Search existing issues** first to avoid duplicates

2. **Use the issue template** if provided
3. Include:
   - Clear description of the problem
   - Steps to reproduce
   - Expected vs. actual behavior
   - System details (hardware version, firmware version, soil conditions)
   - Relevant data files or screenshots

24.7 Code of Conduct

- Be respectful and constructive
- Focus on the technical merits
- Welcome newcomers
- Acknowledge contributions from others

24.8 Recognition

Contributors are recognized in:

- The project README
- Release notes for significant contributions
- Academic publications when appropriate (with permission)

24.9 Questions?

- Open a discussion on GitHub Discussions
- Tag your issue with "question" for general inquiries
- For sensitive matters, contact the maintainers directly

24.10 License

By contributing, you agree that your contributions will be licensed under the same license as the project (see repository for details).

25 Firmware

25.1 Overview

This section documents the HIRT firmware architecture and development environment. The firmware controls data acquisition, probe communication, and system coordination.

> **Documentation Status**
>
> Firmware documentation is under development. This section will be expanded as the firmware matures through validation testing.

25.2 Architecture Overview

The HIRT system uses a distributed architecture:

```
+-------------------+     +-------------------+
|   Host System     |-----|     Zone Hub      |
|  (Laptop/PC)      | USB |  (Controller)     |
+-------------------+     +---------+---------+
                                    | RS-485 Bus
                      +-------------+-------------+
                      |             |             |
                +-----+-----+ +----+----+ +-----+-----+
```

```
|  Probe 1   | |  Probe   | |  Probe N   |
|  (Node)    | |   ...    | |  (Node)    |
+-----------+ +---------+ +-----------+
```

25.2.1 Components

Host System: Laptop or dedicated controller running acquisition software. Sends commands and receives data over USB.

Zone Hub: Central coordination unit. Manages probe addressing, measurement sequencing, and data aggregation. Based on ARM Cortex-M4 microcontroller.

Probe Nodes: Distributed sensing units. Each contains TX/RX coils (MIT), ring electrodes (ERT), signal conditioning, and ADC. Based on low-power microcontroller.

25.3 Communication Protocol

25.3.1 Physical Layer

- **Bus:** RS-485 differential signaling
- **Baud rate:** 115200 (default), configurable to 921600
- **Topology:** Daisy-chain with termination resistors
- **Cable:** Shielded twisted pair, max 100m total bus length

25.3.2 Message Format

```
[START] [ADDR] [CMD] [LEN] [DATA...] [CRC16] [END]
  0x02   1 byte 1 byte 1 byte  0-255   2 bytes 0x03
```

25.3.3 Commands

Code	Command	Description
0x10	PING	Probe presence check
0x20	CONFIG	Set operating parameters
0x30	MIT_TX	Activate MIT transmitter
0x31	MIT_RX	Read MIT receiver data
0x40	ERT_INJ	Activate ERT current injection
0x41	ERT_MEAS	Read ERT voltage measurement
0x50	STATUS	Read probe status and diagnostics
0x60	CAL	Run calibration routine

25.4 Measurement Sequencing

25.4.1 MIT Acquisition Cycle

```
For each frequency in [2kHz, 5kHz, 10kHz, 20kHz, 50kHz]:
    For each TX_probe in active_probes:
        1. Send MIT_TX command to TX_probe
        2. Wait for TX stabilization (10ms)
        3. For each RX_probe in (active_probes - TX_probe):
            a. Send MIT_RX command to RX_probe
            b. Receive amplitude + phase data
        4. Deactivate TX
```

25.4.2 ERT Acquisition Cycle

```
For each injection_pattern in selected_patterns:
    1. Send ERT_INJ command to injection probes
    2. Wait for current stabilization (50ms)
```

```
3. For each sensing_probe in available_probes:
   a. Send ERT_MEAS command
   b. Receive voltage measurement
4. Deactivate injection
5. Repeat with reversed polarity
```

25.5 Development Environment

25.5.1 Toolchain

- **IDE:** PlatformIO (recommended) or Arduino IDE
- **Compiler:** ARM GCC for Zone Hub, AVR GCC for Probe Nodes
- **Debug:** J-Link or ST-Link for JTAG/SWD debugging

25.5.2 Building Firmware

```
# Zone Hub firmware
cd firmware/zone_hub
platformio run

# Probe Node firmware
cd firmware/probe_node
platformio run
```

25.5.3 Uploading Firmware

```
# Zone Hub (via ST-Link)
platformio run --target upload

# Probe Node (via bootloader)
platformio run --target upload --upload-port /dev/ttyUSB0
```

25.6 Configuration Parameters

25.6.1 Zone Hub Configuration

Parameter	Default	Range	Description
`bus_baud`	115200	9600-921600	RS-485 baud rate
`mit_settle_ms`	10	1-100	TX stabilization time
`ert_settle_ms`	50	10-500	Current stabilization time
`timeout_ms`	100	10-1000	Probe response timeout
`retry_count`	3	0-10	Communication retries

25.6.2 Probe Node Configuration

Parameter	Default	Range	Description
`node_addr`	0x01	0x01-0x20	RS-485 bus address
`tx_current_mA`	10	1-50	MIT TX coil current
`ert_current_mA`	1.0	0.1-2.0	ERT injection current
`adc_averaging`	16	1-256	ADC samples to average
`cal_offset`	0	-1000-1000	Calibration offset

25.7 Calibration Routines

25.7.1 Self-Calibration

The firmware includes self-calibration routines:

1. **TX Current Calibration:** Adjusts DAC output to achieve target current
2. **ADC Offset Calibration:** Measures and stores zero-input offset
3. **Gain Calibration:** Uses reference signal to calibrate gain

25.7.2 Factory Calibration

Full calibration requires:

1. Precision current measurement for TX calibration
2. Known reference targets for response calibration
3. Temperature chamber for drift characterization

See Build Guide: Calibration for procedures.

25.8 Error Handling

25.8.1 Error Codes

Code	Name	Description	Recovery
0x01	TIMEOUT	No probe response	Retry, check connections
0x02	CRC_ERR	Data corruption	Retry, check cable
0x03	OVERLOAD	TX current overload	Reduce current setting
0x04	ADC_SAT	ADC saturation	Reduce gain or signal
0x05	TEMP_WARN	Temperature warning	Allow cooling
0x06	CAL_INVALID	Invalid calibration	Recalibrate

25.8.2 Watchdog and Recovery

- Hardware watchdog timer (2 second timeout)
- Automatic bus reset on repeated communication failures
- State machine returns to IDLE on unrecoverable errors

25.9 Power Management

25.9.1 Operating Modes

Mode	Current Draw	Description
Active	50-100 mA/probe	Full measurement
Standby	5 mA/probe	Awaiting commands
Sleep	0.1 mA/probe	Low-power wait

25.9.2 Battery Considerations

For portable operation:

- Use lithium battery pack (12V nominal)
- Enable sleep mode between measurement cycles
- Target: 8 hours operation from 10 Ah battery

25.10 Version History

Version	Date	Changes
1.0.0	TBD	Initial release
0.9.0	Development	Beta testing

25.11 Future Development

Planned firmware improvements:

- ☐ Over-the-air firmware update via bootloader
- ☐ Adaptive sampling rate based on signal quality
- ☐ Built-in reciprocity checking
- ☐ Real-time data quality indicators
- ☐ Temperature compensation algorithms

26 Data Formats

26.1 Overview

This section specifies the data formats and file organization for HIRT measurements. Consistent data formats ensure reliable post-processing and long-term data management. For field acquisition procedures, see the Data Acquisition section.

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.

26.2 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)

26.2.1 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`
- Geometry: `survey_geometry_{date}.csv`

26.3 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.

Table 140: *MIT record format fields*

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")

Field	Description	Units/Format
freq_hz	Measurement frequency	Hz
amp	Signal amplitude	V or normalized
phase_deg	Phase angle	Degrees
tx_current_mA	TX coil current	mA

26.3.1 Example MIT Record

```
timestamp,section_id,zone_id,tx_probe_id,rx_probe_id,freq_hz,amp,phase_deg,tx_current_mA
2024-03-15T10:30:15Z,S01,ZA,P01,P02,2000,0.0125,45.2,10.5
2024-03-15T10:30:16Z,S01,ZA,P01,P02,5000,0.0098,52.1,10.5
2024-03-15T10:30:17Z,S01,ZA,P01,P02,10000,0.0072,61.8,10.4
```

26.4 ERT Record Format

ERT measurements record the voltage response to injected current, capturing the electrode geometry and the resulting potential. HIRT uses a sequential ring-pair measurement approach where current is injected between two rings on one probe, and voltage is measured at corresponding ring positions on adjacent probes.

i ERT Electrode Configuration: Ring-Pair Sequential Measurements

HIRT's borehole geometry uses a simplified three-electrode approach per measurement:

- **A (inject_pos):** Current injection ring (e.g., Ring A at 0.5m on Probe P01)
- **B (inject_neg):** Current return ring (e.g., Ring B at 1.5m on Probe P01, or ring on adjacent probe)
- **M (sense):** Voltage measurement ring (e.g., Ring A at 0.5m on Probe P02)

The reference potential (N) is implicitly the surface ground connection shared by all probes.

Table 141: *ERT record format fields. Probe/ring IDs use format P{nn}_R{A|B|C} to identify both probe number and ring position.*

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/ring ID	String (e.g., P01_RA)
inject_neg_id	Negative current probe/ring ID	String (e.g., P01_RB)
sense_id	Voltage sensing probe/ring ID	String (e.g., P02_RA)
volt_mV	Measured voltage (vs. ground)	mV
current_mA	Injected current	mA
polarity	Current direction	+1 or -1
notes	Additional notes	Free text

26.4.1 Example ERT Record

```
timestamp,section_id,inject_pos_id,inject_neg_id,sense_id,volt_mV,current_mA,polarity,notes
2024-03-15T10:45:12Z,S01,P01_RA,P01_RB,P02_RA,12.5,1.2,+1,
2024-03-15T10:45:13Z,S01,P01_RA,P01_RB,P02_RB,8.3,1.2,+1,
2024-03-15T10:45:14Z,S01,P01_RA,P01_RB,P03_RA,6.1,1.2,+1,
2024-03-15T10:45:15Z,S01,P01_RA,P01_RB,P02_RA,-12.4,1.2,-1,reversed polarity
```

26.5 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.

Table 142: *Probe registry fields*

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

26.5.1 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,
```

26.6 Survey Geometry File

The survey geometry file links probe identifiers to their actual field positions.

Filename convention: `survey_geometry_{YYYY-MM-DD}.csv`

Field	Description	Units
probe_id	Probe identifier (matches registry)	String
x_m	X position from grid origin	meters
y_m	Y position from grid origin	meters
z_surface_m	Ground surface elevation (relative)	meters
z_tip_m	Probe tip depth below surface	meters (negative)
status	Deployment status	ACTIVE / PARTIAL / SKIPPED
notes	Field observations	Free text

26.6.1 Example Survey Geometry File

```
probe_id,x_m,y_m,z_surface_m,z_tip_m,status,notes
P01,0.00,0.00,0.00,-3.00,ACTIVE,reference origin
P02,2.05,0.12,0.00,-2.95,ACTIVE,offset 12cm for surface root
P03,4.00,0.00,0.00,-3.00,ACTIVE,
P04,6.00,0.00,0.00,-3.00,ACTIVE,
P05,,,,,SKIPPED,large oak tree at position
P06,1.85,1.92,0.15,-2.10,PARTIAL,hit rock layer at 2.1m
P07,4.00,2.00,0.08,-3.00,ACTIVE,
P08,6.10,2.05,-0.05,-3.00,ACTIVE,minor offset for puddle
```

26.7 Metadata Requirements

26.7.1 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

26.7.2 Measurement Parameters

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

26.8 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.

26.9 Data Storage Best Practices

26.9.1 File Organization

Organize survey data in a hierarchical directory structure:

```
data/
+-- 2024-03-15/
|   +-- MIT_S01_2024-03-15.csv
|   +-- MIT_S02_2024-03-15.csv
|   +-- ERT_S01_2024-03-15.csv
|   +-- ERT_S02_2024-03-15.csv
|   +-- field_log_2024-03-15.txt
+-- survey_geometry_2024-03-15.csv
+-- probe_registry.csv
```

26.9.2 Backup Procedures

- Copy raw data to at least two independent storage locations
- Verify file integrity using checksums (MD5 or SHA-256)
- Store originals in read-only archive locations
- Create processed copies for any transformations

27 Roadmap

27.1 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.

27.2 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.

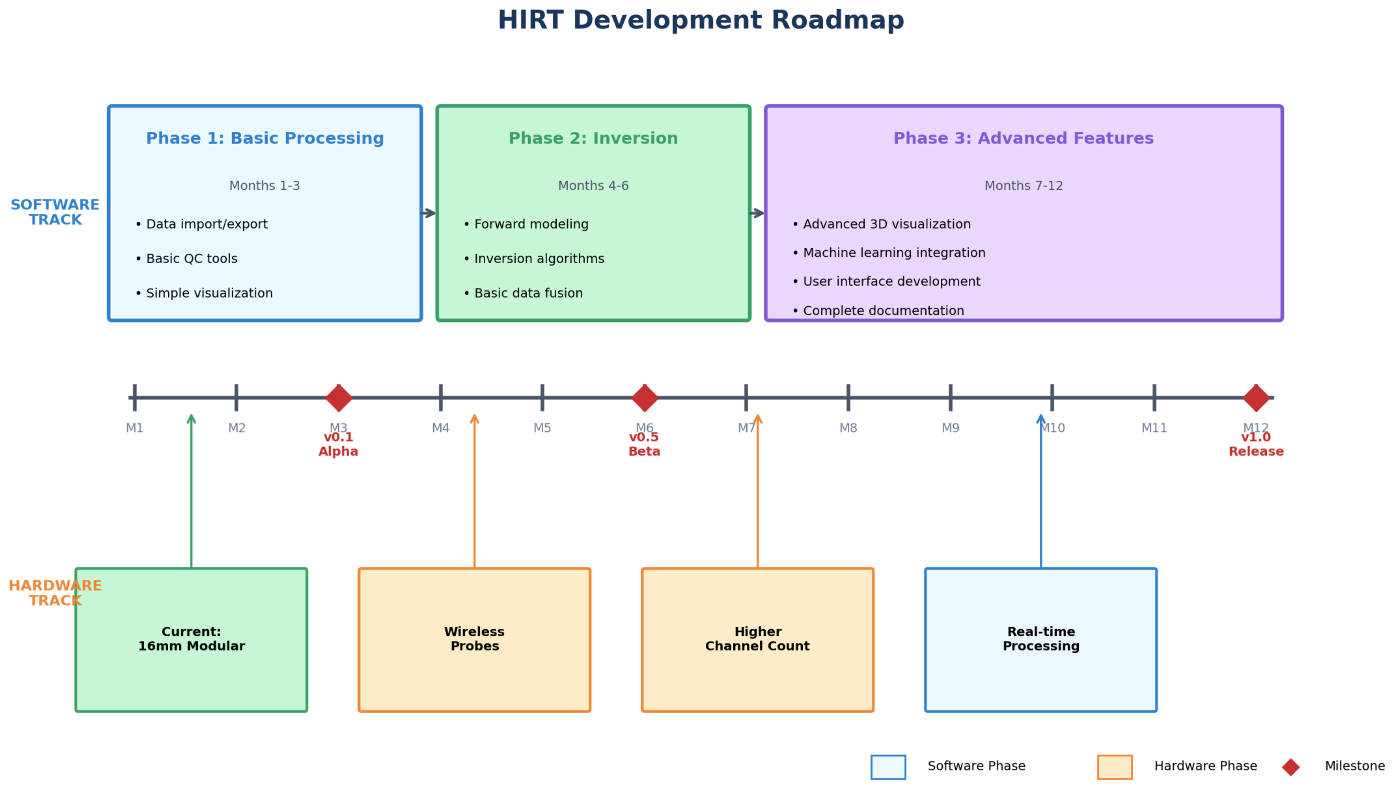

Figure 18: *Development roadmap showing software phases (top track) and hardware improvements (bottom track). Key milestones include Alpha (v0.1) at month 3, Beta (v0.5) at month 6, and full Release (v1.0) at month 12.*

27.3 Firmware Development (Phase 2)

The HIRT hardware system requires embedded firmware to operate. This firmware development is explicitly **Phase 2** of the project—the hardware design documented in this whitepaper can be built and bench-tested, but firmware is required for integrated field operation.

27.3.1 Firmware Scope and Architecture

Table 144: *Firmware module breakdown and priorities*

Module	Function	Priority
DDS Control	AD9833 SPI initialization, frequency programming, multi-frequency sweep	Core
ADC Interface	ADS1256 SPI driver, differential sampling, data buffering	Core
Lock-In DSP	Digital IQ demodulation, amplitude/phase extraction	Core
Multiplexer Control	CD74HC4067 address sequencing, probe selection logic	Core
ERT Sequencer	Current source control, polarity reversal timing, compliance monitoring	Core
USB Data Logger	Real-time CSV streaming, measurement timestamping	Secondary
Configuration UI	Serial command interface, parameter storage	Secondary

27.3.2 Target Platform: ESP32

The hardware design specifies the **ESP32-WROOM-32** module as the MCU platform, selected for:

- Dual-core 240 MHz processor (adequate for lock-in DSP)
- Built-in WiFi/BLE for future wireless data transfer
- 520 KB SRAM for measurement buffering
- Arduino and ESP-IDF toolchain support
- Wide availability and low cost (<$5 per module)

27.3.3 Firmware Repository Status

> Current Status: Not Yet Published
>
> Firmware development is scheduled to begin after hardware validation is complete. The planned repository location is:
> **Planned Repository:** `github.com/hirt-project/hirt-firmware`
> Contributors interested in early development should contact the project maintainers. Firmware will be released under MIT License to match the hardware documentation.

27.3.4 Bench Testing Without Firmware

Builders can validate hardware subsystems before firmware is available:

1. **DDS Testing:** Use Arduino Uno with AD9833 library to verify sine wave generation
2. **ADC Testing:** Use Arduino with ADS1256 library to verify signal acquisition
3. **Coil Testing:** Apply known signal to TX coil, measure RX coil with oscilloscope
4. **ERT Current Source:** Verify compliance voltage and current accuracy with resistor loads
5. **Multiplexer Testing:** Manually step through channels with GPIO to verify routing

These individual tests confirm hardware function before integrated firmware is available.

27.4 Software Development Pipeline

27.4.1 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

27.4.2 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

27.4.3 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

27.4.4 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

27.5 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.

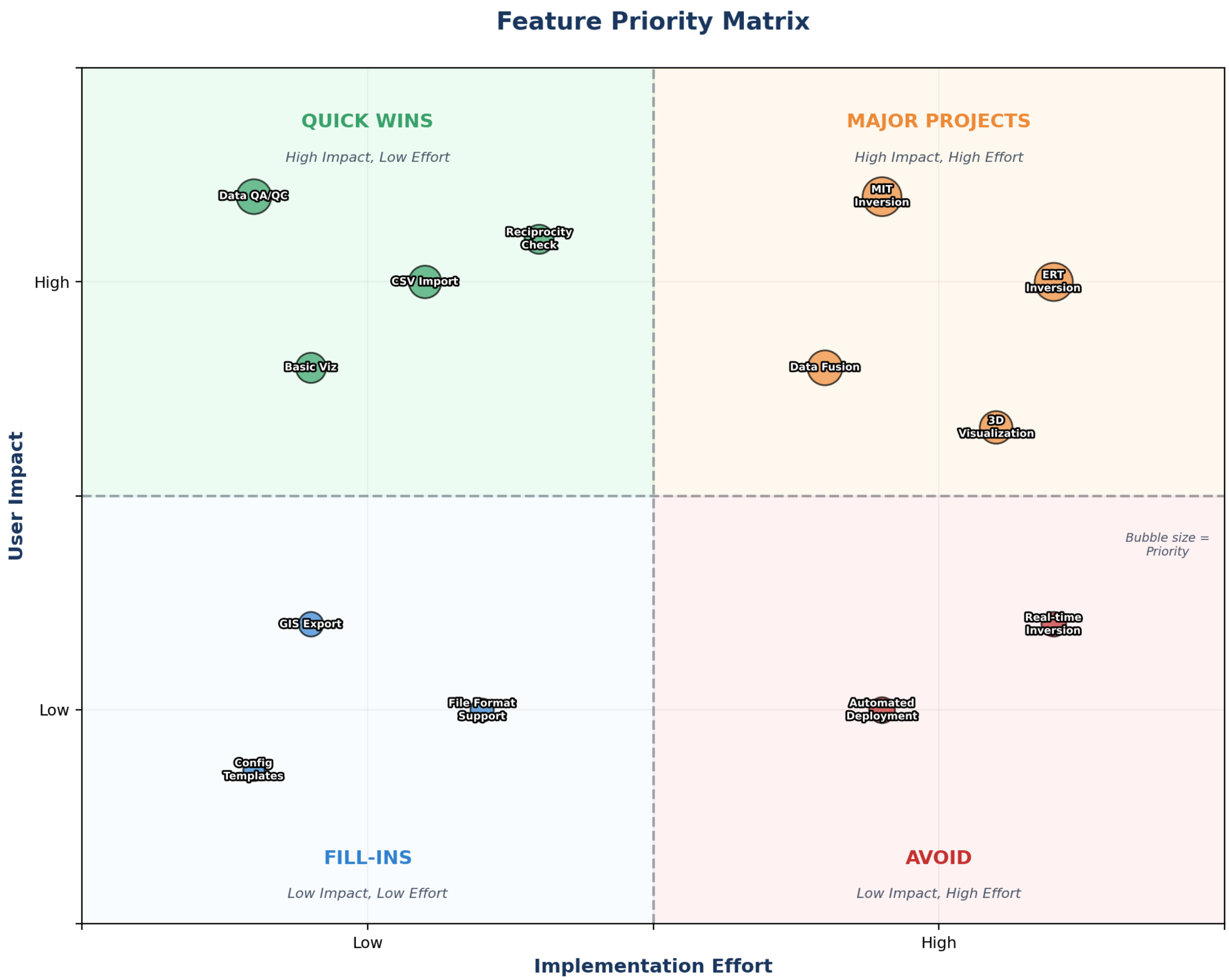

Figure 19: *Feature priority matrix categorizing development items by implementation effort (x-axis) and user impact (y-axis). Bubble size indicates relative priority. Quick wins include data QA/QC and basic visualization; major projects include MIT/ERT inversion and 3D visualization.*

27.6 Software Architecture

27.6.1 Language and Library Considerations

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

Table 145: *Language options for software development*

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

27.6.2 Key Libraries and Tools

Table 146: *Recommended libraries and tools for HIRT software*

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

27.7 Planned Hardware Improvements

27.7.1 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

27.7.2 Higher Channel Count

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

27.7.3 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)

27.8 Forward Modeling and Validation

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

Table 147: *Recommended forward modeling tools*

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

27.8.1 HIRT-Relevant Tutorials and Workflows

The following tutorials from these packages are directly applicable to HIRT data processing:

SimPEG Tutorials:

- *DC Resistivity 3D Inversion* - Demonstrates `Simulation3DCellCentered` for borehole data
- *OcTree Mesh for DC/IP* - Efficient mesh refinement near electrodes
- *Electrode Draping* - Handles topography with `drape_electrodes_on_topography`

pyGIMLi Tutorials:

- *Crosshole ERT* - Published example with 144 electrodes across 9 boreholes, 1,256 measurements
- *Timelapse ERT* - `CrossholeERT` class for temporal monitoring applications
- *Regularization Options* - zWeight adjustment for anisotropic smoothing

empymod Applications:

- Loop source modeling for 2-50 kHz range (HIRT operating frequencies)
- Layered-earth forward modeling validates HIRT physics assumptions
- In-phase/Quadrature decomposition: Real component = resistive response, Imaginary component = inductive response

27.8.2 Data Export Integration Path

HIRT field data should be exported in standard formats compatible with inversion packages:

1. **HIRT Field Data** (.csv) - Raw measurements from probes
2. **Format Conversion** - Python script transforms to target format
3. **Target Formats:**
   - SimPEG: Survey + Data objects
   - pyGIMLi: DataContainerERT
   - empymod: 1D layered parameters
4. **Inversion / Forward Modeling** - Run with chosen package
5. **Output:** 3D Model + Uncertainty Estimates

27.8.3 Open-Source Hardware Reference: OhmPi

The OhmPi project (ohmpi.org) provides a valuable reference design for open-source resistivity instrumentation:

Table 148: *Comparison of OhmPi and HIRT ERT specifications*

Specification	OhmPi	HIRT ERT
Architecture	Raspberry Pi + ADS1115 ADC	Custom MCU + ADC
Channels	32 electrodes standard	Scalable, 4+ probes
Current range	0.1-80 mA	0.5-2 mA (safety limited)
Voltage range	0.001-12 V	Similar
Cost	<$500 (32 channel)	Target similar
Philosophy	Open-source, DIY	Open-source, DIY

OhmPi demonstrates that research-grade resistivity measurements are achievable with commodity electronics. Their Raspberry Pi architecture and ADS1115 ADC approach may inform future HIRT development, particularly for the base station/hub electronics.

27.8.4 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

27.9 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)

27.10 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)

Note

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

27.11 Documentation Needs

27.11.1 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

27.11.2 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

27.12 Software References

1. Cockett, R., Kang, S., Heagy, L. J., Pidlisecky, A., & Oldenburg, D. W. (2015). SimPEG: An open source framework for simulation and gradient based parameter estimation in geophysical applications. *Computers & Geosciences*, 85, 142-154. DOI: 10.1016/j.cageo.2015.09.015
2. Rücker, C., Günther, T., & Wagner, F. M. (2017). pyGIMLi: An open-source library for modelling and inversion in geophysics. *Computers & Geosciences*, 109, 106-123. DOI: 10.1016/j.cageo.2017.07.011
3. Werthmüller, D. (2017). An open-source full 3D electromagnetic modeler for 1D VTI media in Python: empymod. *Geophysics*, 82(6), WB9-WB19. DOI: 10.1190/geo2016-0626.1

Part VI
Appendices

28 Glossary

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.

28.1 Acronyms and Terms

28.1.1 A-D

Analog-to-Digital Converter (ADC): 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.

Bill of Materials (BOM): 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.

Delta-Sigma ADC: Type of analog-to-digital converter that uses oversampling and noise shaping to achieve high resolution; commonly used in precision measurement applications.

Direct Digital Synthesis (DDS): Technique for generating precise frequency signals digitally; used in HIRT to create stable excitation waveforms for both MIT and ERT channels.

28.1.2 E-H

Electrical Resistivity Tomography (ERT): 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.

Howland Current Source: Precision current source circuit topology used in the ERT channel to inject controlled current into the soil independent of load impedance.

28.1.3 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).

28.1.4 M-P

Magnetic Induction Tomography (MIT): Low-frequency electromagnetic method using coils; measures amplitude and phase changes caused by conductive objects.

Microcontroller Unit (MCU): 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.

28.1.5 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.

Receive/Receiver (RX): 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.

28.1.6 U-Z

Transmit/Transmitter (TX): Transmitting coil or probe that generates signals.

Tomography: Imaging method that reconstructs 3D structure from multiple measurements; similar to medical CT scanning.

Unexploded Ordnance (UXO): Live explosive devices that may be present at WWII sites; requires EOD clearance before deployment.

28.2 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.

Signal-to-Noise Ratio (SNR): Ratio of signal strength to noise level; higher SNR = better data quality.

28.3 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.

29 Quick Reference

29.1 Overview

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.

29.2 Power-Up Sequence

The HIRT quick setup sequence consists of seven steps:

1. **Connect Trunk Cables** - Attach trunk cables from Zone Hubs to Central Hub
2. **Connect Probes** - Connect probe cables to Zone Hubs
3. **Power ON Base Hub** - Turn on the Central Hub power switch
4. **Wait 15s for Init** - Allow system initialization to complete
5. **Verify "Ready" LED** - Confirm the Ready LED is solid green
6. **Run System Diagnostic** - Execute the built-in diagnostic test
7. **Start Measurement** - Begin data acquisition

> **Note**
>
> Total Setup Time: approximately 2-3 minutes (excluding probe installation)

29.3 Key Parameters

29.3.1 MIT Parameters

Parameter	Value
Frequency	2-50 kHz
TX Current	10-50 mA
Integration	1-5 sec

29.3.2 ERT Parameters

Parameter	Value
Injection	0.5-2 mA
Ring Positions	0.5, 1.5, 2.5 m
Polarity Reversal	Every 2 sec

29.3.3 Grid Layout

Parameter	Value
Spacing	2 meters
Standard Grid	5 x 5 (25 probes)
Probe Depth	2.5-3 m

29.4 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
```

29.5 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

29.6 Cable Color Code

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

29.7 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

29.8 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

29.9 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

ℹ Note

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

30 Field Checklists

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.

30.1 16.1 Pre-Deployment Checklist

30.1.1 Permits and Legal

> ⚠ Warning
>
> ☐ Permits/ethics & UXO clearance confirmed
> ☐ Site access permissions obtained
> ☐ Team members briefed on legal/ethical requirements
> ☐ Emergency contacts documented

30.1.2 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)

30.1.3 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)

30.1.4 Documentation

☐ Field log templates prepared
☐ Probe registry updated
☐ Site maps/plans available
☐ Previous survey data (if applicable)

30.2 16.2 On-Site Checklist

30.2.1 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

30.2.2 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

30.2.3 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

30.2.4 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

30.2.5 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

30.3 16.3 Post-Deployment Checklist

30.3.1 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

30.3.2 Equipment Care

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

30.3.3 Post-Survey Documentation

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

30.3.4 Follow-Up Actions

- ☐ Review data quality
- ☐ Identify any missing measurements
- ☐ Plan next steps (additional sections, processing)
- ☐ Schedule equipment maintenance
- ☐ Update procedures based on experience

30.4 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.

30.4.1 Safety Incidents

Warning

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

30.4.2 Equipment Failure

Caution

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

30.4.3 Data Loss Response

Caution

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

30.5 16.5 UXO Site Safety Visual

For humanitarian demining or UXO-sensitive sites, the following checklist provides critical safety requirements that must be completed before operations begin.

! UXO Site Safety Checklist

Before ANY field operations at UXO-sensitive sites:
☐ EOD clearance certificate obtained
☐ Safety briefing completed for all team members
☐ Designated safe zones marked
☐ Emergency evacuation routes identified
☐ Communication protocols established
☐ Personal protective equipment verified
☐ First aid capabilities confirmed on-site

30.6 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.

30.6.1 Daily Entry

Field	Value
Date	______
Site	______
Section	______
Team	______
Weather	______
Soil conditions	______

30.6.2 Measurements

Field	Value
Probes deployed	______
MIT frequencies	______
ERT baselines	______
Start time	______
End time	______
Issues encountered	______

30.6.3 Notes

____

____

____

____

____

____

Completed by: ______________________

Signature: ______________________

Date: ______________________

30.7 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

31 Regulations and Legal Requirements

31.1 Overview

This appendix covers legal, regulatory, and ethical requirements for HIRT deployment. For operational safety procedures, see Getting Started: Safety.

31.2 "Permit to Dig" Requirements

In jurisdictions such as the UK (under **CIRIA C681**) and EU conflict zones, a "Permit to Dig" is strictly conditional.

Workflow for HIRT Deployment:

1. **Detailed Risk Assessment (DRA):** Must be completed by a competent UXO specialist before any site work
2. **Non-Intrusive Survey:** Surface magnetometry to clear the general area
3. **Intrusive MagCone/Probe:** Use passive magnetometry to clear the specific probe insertion point to depth
4. **Certificate:** Obtain a *UXO Clearance Certificate* for the specific coordinate
5. **Permit Issuance:** The Permit to Dig is issued only after the Clearance Certificate is attached

31.3 Forensic Data Integrity and Chain of Custody

HIRT surveys conducted in support of criminal investigations, human rights documentation, or conflict archaeology must adhere to forensic standards that ensure data integrity and admissibility in legal proceedings.

31.3.1 Why Chain of Custody Matters

HIRT-derived evidence may support criminal prosecutions, civil litigation, or international tribunals investigating war crimes. Data integrity depends on documented procedures satisfying three core requirements:

Authenticity: Proof that data originated from the stated location and time, collected by identified personnel using verified equipment.

Continuity: An unbroken record of who handled the data, when transfers occurred, and what actions were performed.

Integrity: Verification that data remains unchanged from collection. Cryptographic hashes (MD5, SHA-256) provide mathematical proof.

31.3.2 Data Collection Protocol

Every forensic HIRT survey must capture comprehensive metadata:

Survey Identification: Use format `[DATE]-[SITE]-[OPERATOR]`, e.g., `20260130-KAMPALA-SMITH`

Temporal Documentation: Embed UTC timestamps in all data files. Record local time zone offset.

Operator Credentials: Record full name, affiliation, and certifications of all personnel.

Equipment Traceability: Log serial numbers of all probes, data loggers, GPS units, and calibration standards.

Instrument Settings: Record all acquisition parameters including frequencies, current levels, and filter settings.

31.3.3 Field Documentation

Site Photography: Capture wide-angle photographs before probe insertion. Document each probe location. Include scale reference and compass orientation.

Geolocation Data: Record GPS coordinates (WGS84) using survey-grade receiver with sub-meter accuracy. Document DOP values.

Environmental Conditions: Log weather, soil moisture, and vegetation type.

Witness Signatures: In some jurisdictions, forensic surveys require independent witness verification.

Field Sketches: Draw scaled diagrams showing probe locations relative to permanent landmarks.

31.3.4 Data Handling Procedures

Original File Preservation: Copy raw data to write-protected media immediately. Never analyze original files.

Cryptographic Hash Verification: Compute MD5 and SHA-256 hashes immediately after collection. Verify before any analysis.

Secure Storage: Use access-controlled, encrypted storage with audit logging. Maintain three independent copies.

Access Logging: Record every access to data files including date, time, user, and actions performed.

31.3.5 Transfer Protocols

Physical Media Transfer: Use chain of custody form. Package in tamper-evident bags with serialized seals.

Digital Transfer: Use encrypted protocols (SFTP, secure cloud). Log transfer events with hash verification.

Third-Party Analysis: Establish written agreements specifying handling requirements and destruction procedures.

International Transfer: Cross-border transfers may trigger export controls and data privacy regulations. Consult legal counsel.

31.3.6 Reporting Requirements

Methodology Section: Describe HIRT measurement principle, configuration, and processing workflow in sufficient detail for independent evaluation.

Software Documentation: Identify all software with version numbers and configuration settings.

Limitations and Uncertainty: State measurement uncertainties, depth resolution limits, and factors affecting interpretation. Provide confidence levels.

Operator Qualifications: Include statement of education, training, and experience.

Peer Review: Consider independent review for high-stakes proceedings.

31.3.7 Chain of Custody Form Template

HIRT Data Chain of Custody Form

Case Identifier: ______________________________ **Survey ID:** ______________________________ **Date of Collection:** ______________________________

____

Evidence Description:

- Data file names: ______________________________
- Number of files: ______________________________
- Storage media: ______________________________
- Total data volume: ______________________________

Hash Values (at time of collection):

- MD5: ______________________________
- SHA-256: ______________________________

____

Transfer Log:

Date/Time	Released By (Signature)	Received By (Signature)	Purpose	Location

____
Special Handling Instructions: ____
Disposition (Final): Returned to originator [ ] Permanently archived [ ] Destroyed [ ]
Date: ______________ Authorized By: ___________________________________

31.4 Applicable Standards

HIRT forensic data handling should align with established standards:

- **ASTM E1492-23**: Standard Practice for Receiving, Documenting, Storing, and Retrieving Evidence in a Forensic Science Laboratory
- **ISO/IEC 27037:2012**: Guidelines for identification, collection, acquisition, and preservation of digital evidence
- **SWGDE Best Practices for Computer Forensics** (Scientific Working Group on Digital Evidence)
- **NIJ Electronic Crime Scene Investigation Guide** (US National Institute of Justice)
- **IMAS 07.11**: International Mine Action Standards for Land Release
- **CIRIA C681**: Unexploded Ordnance (UXO) A Guide for the Construction Industry (UK)

31.5 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.