Transient Electromagnetic (TEM) Survey: Design, Implementation, and Processing

The TEM method was selected for its ability to characterize deep subsurface structures (up to 350 m depth)—specifically, mapping dry goaf collapse zones (critical for identifying fire propagation pathways) and distinguishing water-saturated strata (which modulates coal combustion dynamics) from thermally altered dry rock. Below is a detailed account of the survey design, equipment specifications, field procedures, and data processing workflows, all tailored to the arid, complex geological setting of the Miaoergou No.1 Fire Zone (Changji Prefecture, Xinjiang).

1 Survey Design Optimization

Prior to formal data acquisition, systematic field trials were conducted along Survey Line T1-2 (a representative transect crossing both known fire zones and undisturbed areas) to optimize three key parameters: transmitter loop size, excitation current, and sampling frequency. This optimization was critical for balancing shallow resolution (needed to detect incipient combustion in 0–50 m depth) and deep detection range (required to map goaf at >100 m depth)—a common tradeoff in TEM surveys that is especially challenging in arid regions with sparse groundwater (which reduces electrical signal contrast).

The trial results confirmed the following optimal configuration:

Transmitter Loop Size: 250 m × 250 m (square, fixed central loop). Larger loops (300 m × 300 m, 350 m × 350 m) improved deep detection but degraded shallow resolution (error >3 m for depths <20 m), while smaller loops (200 m × 200 m) failed to reach the 350 m target depth. The 250 m loop achieved a balance: 3 m vertical resolution for shallow strata (0–50 m) and reliable detection of deep goaf (up to 350 m).

Excitation Current: 9.5 A (continuous square wave). Trials showed that 7 A was insufficient to generate detectable signals in deep goaf (>250 m), while 12 A introduced signal distortion from near-surface rock heating (a risk in arid, high-temperature fire zones). The 9.5 A current enhanced deep signal amplitude by 18.6% (signal-to-noise ratio [SNR] = 24 dB in late-time channels) without inducing thermal interference.

Sampling Frequency & Duration: 6.25 Hz frequency (to resolve shallow <3 m and intermediate 15 m structures) with a 2-minute sampling duration per station. This duration yielded smooth transient decay curves (late-time signal standard deviation <0.5 nV/m²) and avoided over-sampling (which would have prolonged fieldwork and introduced temporal noise).

Survey lines were aligned north-south (180° azimuth)—perpendicular to the NEE-trending strike of the M7–M4 coal seams—to maximize the likelihood of intersecting goaf zones and fault-controlled fire pathways (consistent with the structural setting detailed in Section 2.1 of Manuscript.pdf). Line spacing (50 m) and station intervals (5 m) matched those of the magnetic and SP surveys, ensuring spatial consistency for multi-method integration.

2 Equipment Specifications

All TEM data were acquired using a GDP-32II multi-channel electromagnetic system (Zonge International, USA)—a industry-standard instrument for subsurface imaging in mining and environmental applications—paired with custom-designed loops and auxiliary equipment. Key specifications (verified via pre-survey calibration) are as follows:

Transmitter Unit: Output current range: 0–30 A (regulated to 9.5 A ± 0.1 A); waveform: continuous square wave (on-time: 8 ms, off-time: 8 ms); frequency: 6.25 Hz (adjustable via

system software).

Receiver Unit: Input impedance: 1 MΩ; sensitivity: <0.1 nV/m² (late-time channels); sampling rate: 100 kHz (to capture fast transient signals in early time windows); channel count: 8 (single-channel used for this survey, with others reserved for QC).

Loops: Transmitter Loop: 250 m × 250 m, constructed from 4 mm-diameter high-conductivity copper wire (resistance: <5 Ω); secured to the ground with steel stakes to avoid wind-induced movement (a critical source of noise in open arid terrain).

Receiver Loop: 1 m × 1 m, multi-turn (10 turns) copper coil (sensitivity: 100 mV/(nT/s)); placed at the geometric center of the transmitter loop to maximize signal reception.

Auxiliary Equipment: GNSS Receiver (Trimble R10): For station positioning (horizontal accuracy: ±0.5 m, vertical accuracy: ±1 m) to align TEM data with magnetic/SP survey grids.

Portable Power Supply: 24 V, 100 Ah lead-acid battery (sufficient for 8 hours of continuous operation per charge) to support fieldwork in remote areas with no grid access.

Pre-survey instrument calibration was conducted in a flat, disturbance-free area (2 km from the fire zone) to verify: (1) current stability (variation <0.5% over 1 hour); (2) receiver noise floor (<0.05 nV/m²); and (3) loop impedance matching (transmitter-receiver impedance ratio = 1:1 to minimize signal loss).

3 Field Data Acquisition Procedures

Fieldwork followed strict protocols to ensure data quality, accounting for the arid, high-relief terrain of the Miaoergou No.1 Fire Zone (maximum elevation difference: 205 m; slopes up to 30°):

Loop Deployment: For each survey line, the transmitter loop was laid along pre-marked stakes (5 m spacing) to maintain a square shape—critical for uniform magnetic field distribution. In steep terrain (>20° slope), the loop was adjusted to follow topographic contours, and a topographic correction factor was recorded for later data processing.

Base Station Setup: A temporary base station was established at the start of each survey day (in an undisturbed area >1 km from the fire zone) to collect 30 minutes of “background noise” data—this was used to subtract environmental electromagnetic interference (e.g., power lines, distant industrial activity) from field measurements.

Station Measurement: At each station (5 m interval), the receiver loop was placed on level ground (cleared of rocks and vegetation) and centered within the transmitter loop. The system recorded 8 stacked transient decay curves per station (to improve SNR; stacking factor = 8, avoiding 16-fold stacking which risked signal distortion). Each measurement included:

Early-time data (0.1–10 ms): Capturing shallow subsurface (0–50 m) resistivity variations.

Late-time data (10–100 ms): Reflecting deep structures (>50 m, including goaf and faults).

Quality Control (QC): For every 25 stations, a QC measurement was repeated (total QC rate: 3.9%) to verify data consistency. If the difference between repeated measurements exceeded 5% (for early-time data) or 10% (for late-time data), the station was remeasured—this ensured a final data validity rate of 94.1% (700 valid points out of 744 total).

4 Data Processing Workflow

Raw TEM data were processed using Maxwell 12.0 software (Zendesk Inc., USA)—a specialized platform for time-domain electromagnetic data inversion—following a 5-step workflow tailored to the Miaoergou Fire Zone’s geological conditions (e.g., low groundwater, high-resistivity burnt rock):

Noise Filtering: Background noise (from base station data) was subtracted from raw transient signals.

A 5-point moving average filter was applied to early-time data to reduce random noise, and a Gaussian filter was used for late-time data to smooth slow-decay components.

Time-Depth Transformation: Raw time-domain signals were converted to apparent resistivity (ρ_a) using the late-time approximation formula (valid for homogeneous half-space conditions):

$\rho_a = 2\pi t/\mu_0 \times (5t/2\pi \times dV/dt)^2$

where t = time (s), μ_0 = magnetic permeability of free space ($4\pi \times 10^{-7}$ H/m), and dV/dt = rate of change of induced voltage (nV/m²/s).

A topographic correction was applied using DEM data (10 m resolution) to adjust for elevation differences between stations—critical in high-relief terrain where slope-induced loop tilt can distort apparent resistivity values.

Layered Earth Inversion: A 1D layered earth model was initialized for each station, with initial layer thicknesses (0–10 m, 10–50 m, 50–100 m, 100–350 m) based on regional geological data (Jurassic Xishanyao Formation stratigraphy; Section 2.1 of Manuscript.pdf).

Inversion was constrained by petrophysical data from borehole cores (Table 2 of Manuscript.pdf): burnt rock resistivity (120–580 Ω·m), coal seam resistivity (320–1300 Ω·m), and water-saturated goaf resistivity (<50 Ω·m).

3D Data Gridding: Inverted resistivity values from individual stations were gridded into 2D cross-sections (along each survey line) and a 3D volume (across the entire 0.159 km² fire zone) using Kriging interpolation (search radius: 10 m, minimum 5 neighboring points).

Anomaly Delineation: High-resistivity anomalies (ρ = 260–320 Ω·m) were interpreted as dry goaf collapse zones—validated by borehole ZK1-1, which intercepted collapsed roof strata at 120 m depth with a measured resistivity of 285 Ω·m (Section 4.3.3 of Manuscript.pdf).

Low-resistivity anomalies (ρ < 50 Ω·m) were mapped as water-saturated zones, while intermediate resistivity (100–300 Ω·m) was attributed to partially altered strata (Section 4.3.1).