

Eliminating Inductive Coupling in Small-Loop TEM Through Differential Measurement with Opposing Coils

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Abstract: The small-loop transient electromagnetic method (TEM) refers to a system in which the coil frame length or diameter is less than 2 m. Due to the inductive effects of the multi-turn coils used for both transmission and reception, the induced electromotive force in the measuring coil increases, causing a reduction in the decay rate and an extension of the shutoff time. This results in coupling between the primary and secondary fields in early-time signals, making them difficult to separate and creating a detection blind spot in the shallow subsurface. The opposing coil TEM transmission and reception method can significantly reduce early-time signal distortion caused by coil inductance. However, this approach is constrained by the physical symmetry of the coil dimensions, which makes it challenging to achieve balance in a zero-field space. By performing both forward and reverse measurements at the same location using the opposing coil setup and calculating the difference between the signals, the inductive coupling between coils at the measurement site can theoretically be eliminated. This eliminates the induced potential of the TEM signal, enhancing the induced electromotive force from the formation. As a result, more accurate resistivity values are obtained, detection blind spots are eliminated, and the resolution in shallow TEM exploration is improved. Field experiments were conducted to validate the method on both high-resistivity and low-resistivity anomalies. The results demonstrated that this method effectively identified a high-resistivity corrugated pipe at a depth of 1.2 m and two low-resistivity gas pipelines at a depth of 2 m, thereby essentially eliminating detection blind spots in the shallow subsurface.

Keywords: opposing coil; coil reversal; inductance; blind spot elimination



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1. Introduction

The transient electromagnetic method (TEM) is a widely used geophysical technique, with its detection depth influenced by factors such as the current magnitude, coil size, number of turns, and winding configuration. Larger currents and coils enable greater detection depths but also lead to larger detection blind spots [1]. TEM is commonly applied in resource exploration [2] and coal mine water hazard detection [3–6] for deep target identification, where the impact of blind spots on the shallow subsurface is generally negligible. However, for shallow investigations, such as urban engineering surveys [7,8], environmental assessments [9], hydrogeological surveys, abandoned pipeline detection, and unexploded ordnance detection [10–13], the primary concern is the resolution of shallow detection, and thus, the issue of blind spots becomes critical.

In shallow TEM applications, small-loop TEM are typically used, referring to systems with loop side lengths or diameters of less than 2 m [14]. These small-loop TEM systems feature more coil turns and a closer spacing between the transmitter and receiver coils, which results in larger detection blind spots. These blind spots are primarily attributed to early signal distortion in the transient field. Early signals are affected by the transient processes of the receiving system and the mutual inductance between the transmitting and receiving coils. To mitigate the impact of the transient process, the receiving system can be tuned to a damped matching state in practical applications. However, the mutual inductance effect between the coils is driven by the coil's internal resistance and the inductance between the coils, which prevents the excitation current from shutting off instantaneously. During the shutoff period, the coupling of the primary and secondary fields distorts the early signals, leading to a loss of shallow subsurface geoelectric information.

To reduce the induced electromotive force in the receiving coil, the transmitting and receiving coils are typically separated [15]. While this separation can mitigate the mutual inductance effect to some extent, its effectiveness is limited. Moreover, the coupling effect of the apparatus becomes more pronounced, weakening the response signal, complicating the anomaly characteristics, and diminishing lateral resolution [16,17].

To reduce shallow detection blind spots, significant advancements have been made in both theoretical research and coil design. Asten M.W. and Price D.G. employed coordinate transformation methods to correct the stepped wave response, treating it as a delayed effect of the step wave response. This approach enabled apparent resistivity calculation or inversion [18]. Eaton and Hohmann developed correction formulas for magnetic induction intensity [19]; however, their method requires a high signal-to-noise ratio, limiting its practical applications. Fitterman D.V. and Anderson W.L. derived correction formulas for stepped wave responses [20], but these were primarily designed for a few typical geoelectric models. The correction coefficients required specific conditions to produce accurate results, making them difficult to apply in real engineering surveys. Smith and Balch observed the entire transient response and recorded the excitation current waveform. They combined theoretical derivations with numerical calculations to determine primary field interference and then remove or correct it from the measured total field [21]. Due to the complexity of actual geological conditions, the real primary field is more complicated than numerical calculations suggest. As a result, the secondary field obtained from this correction process deviates from the actual field. These theoretical approaches to early signal correction face significant challenges in practical applications, particularly in fully eliminating the effects of inductance.

In coil design, efforts have focused on positioning the transmitter and receiver coils to minimize mutual inductance effects. These designs are known as weak-coupling coils and include various types: Curved coils used in airborne TEM [22,23], Gradient coils [24], Opposing coils [25,26], Weak-coupling coils with crossed rings [14], and Coaxial zero magnetic flux coils [27]. These coil designs significantly reduce the shallow detection blind spot issue. However, the principle of decoupling necessitates increasing the number of turns in the receiving coil to expand its receiving area. This, in turn, increases the coil's self-inductance and rapidly reduces its bandwidth. While these coil designs have greatly reduced inductance between coils, factors such as materials and manufacturing processes prevent the complete elimination of inductance issues. As a result, detection resolution in the ultra-shallow range of 1 to 2 m is still affected.

The response signal in the ultra-shallow range is heavily influenced by inductance in the early-time signals. To completely eliminate the inductive effect on the secondary field, this study utilizes the opposing coil TEM method, which exploits the fact that the transmitting field in both directions of the opposing coils is identical. By performing forward and

reverse measurements at the same point and subtracting the signals, the inductive signal can theoretically be eliminated. This method not only eliminates the inductive signal but also enhances the response signal. Section 2 of the manuscript introduces the principle of our method and discusses the apparent resistivity calculation based on this approach. Furthermore, it presents experimental results from physical tests on high-resistivity and low-resistivity anomalies, demonstrating excellent detection performance.

2. Materials and Methods

2.1. The Principle of Opposing Coil

The principle of the opposing coil method is illustrated in Figure 1. Two transmitter coils, TX1 and TX2, with identical parameters, are connected in series and positioned concentrically with their winding directions reversed. When current flows through the coils, the currents in the upper and lower coils flow in opposite directions. As a result, the magnetic fields generated by the coils in the central region are of equal strength but opposite directions, effectively canceling each other out and creating a zero magnetic flux plane. When the receiver coil (RX) is placed on this zero magnetic flux plane for signal reception, it is unaffected by the inductive effects of the transmitter coils. The opposing coil configuration is a type of weak-coupling coil design, which significantly reduces inductive interference. In principle, it can completely eliminate inductance-related issues; however, due to material and manufacturing constraints, it is not possible to entirely eliminate inductance.

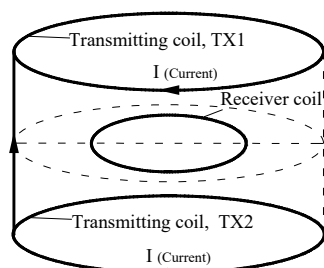


Figure 1. Schematic of the Opposing Coil Configuration.

2.2. The Method of Inductance Elimination in Opposing Coil Differential Measurement

After the current of the opposing coil is turned off, the measured transient field signal is a linear superposition of the coil's inductance, the secondary field response of the geological body, and noise. Suppose the mutual inductance voltage generated by the mutual inductance effect between the transmitting and receiving coils after the opposing coil is powered is denoted as

$$u_{MR_x T_x} = \pm M \frac{di_{T_x}}{dt}, \quad (1)$$

$$M = \frac{\mu_0 \pi R_1^2 N_1 N_2}{l} \left(\frac{R_2^2}{(R_1^2 + R_2^2)} \right)^{3/2}, \quad (2)$$

where μ_0 is the permeability of free space, N_1 and N_2 represent the number of turns of the two coils, l is the length of the coil, R_1 and R_2 represent the radii of the two coils, M is the mutual inductance coefficient of the coils [28], and i_{T_x} is the transmitting current. The “ $\pm$ ” sign is related to the direction of the current, the relative position of the coils, and the winding direction.

The current induced in the receiving coil by the mutual inductance voltage is represented as i_{Rx} , and the self-inductance voltage generated by i_{Rx} in the receiving coil is given as u_{LRx} .

$$u_{LRx} = -L \frac{di_{Rx}}{dt}, \quad (3)$$

$$L = \mu_0 \cdot N_1 N_2 \cdot A / l, \quad (4)$$

where A is the cross-sectional area of the coil, L represents the self-inductance of the coil, N_1 and N_2 represent the number of turns of the two coils, l is the length of the coil, The “−” sign indicates that the self-induced voltage always opposes the change in current within the original circuit. The total inductive interference is denoted as u_{ML} , and the relationship is given as follows:

$$u_{ML} = u_{MRxTx} + u_{LRx} = \pm M \frac{di_{Tx}}{dt} - L \frac{di_{Rx}}{dt}, \quad (5)$$

Without considering noise, the voltage signals measured before and after flipping the transmitter coil are denoted as $u_1(t)$ and $u_2(t)$, respectively. These signals contain the pure geological target responses, represented by $u_{\tau 1}(t)$ and $u_{\tau 2}(t)$, and the interference voltage signals caused by mutual inductance, denoted as u_{ML1} and u_{ML2} . The relationship between these signals is given by

$$u_1(t) = u_{\tau 1}(t) + u_{ML1}, \quad (6)$$

$$u_2(t) = u_{\tau 2}(t) + u_{ML2}, \quad (7)$$

Based on the principle of the opposing coil, the direction of the magnetic field generated by the transmitting coil remains consistent and does not change with the position of the coil. Therefore, after completing a measurement, if the transmitting coil is flipped 180° at the same position and the measurement is repeated with the same parameters, the properties of the transmitted field remain unchanged, and the response signal from the geological body is also identical. Consequently, the inductive signals u_{ML} before and after flipping the coil device are the same, i.e., $u_{ML1} = u_{ML2}$. However, after flipping the device, the relative position of the receiving coil is also inverted by 180° , causing the direction of the induced current generated by the geological body's response signal in the coil to be opposite, as shown in Figure 2. This will result in $u_{\tau 1}(t)$ and $u_{\tau 2}(t)$ having opposite signs. This is a crucial point; therefore, the signals after flipping the coil will have the opposite sign compared to those before flipping. The relationship between $u_{\tau 1}(t)$ and $u_{\tau 2}(t)$ is given by Equation (8).

$$u_{\tau 2}(t) = -k u_{\tau 1}(t), \quad k > 0 \quad (8)$$

The consistency factor for the measurement system after a 180° flip indicates how well the measurements align. When there is perfect alignment, $k = 1$. After calculating the difference, the effective signal from the formation is doubled. If there are deviations due to the flip, k fluctuates around 1 and remains greater than 0, ensuring that the effective signal from the formation does not attenuate. The self-inductance and mutual inductance effects between the transmitting and receiving coils are completely eliminated. Thus, the voltage signal difference $\Delta u(t)$ measured at the same position before and after flipping the coil device by 180° is given by Equation (9).

$$\Delta u(t) = (1 + k) u_{\tau 1}(t), \quad (9)$$

where $k > 0$, the decay segment signal $u_{\tau 1}(t)$ is positive,

$$\text{or } \Delta u(t) = -(1 + k) u_{\tau 1}(t), \quad (10)$$

the decay segment signal $u_{\tau 1}(t)$ is negative.

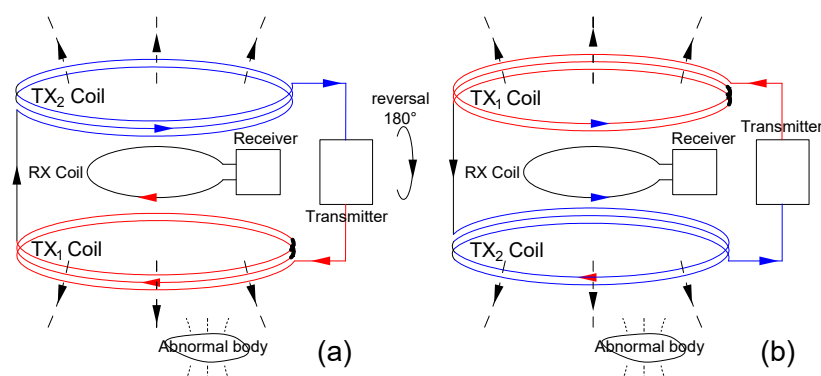


Figure 2. Schematic diagram illustrating the principle of opposing coil measurements in both forward and reverse directions. The red and blue coils represent a pair of transmitting coils, which have the same number of turns, but their winding directions are reversed and they are connected in series within the circuit. In (a), the relative position of the red and blue coils is shown for a specific configuration, where the blue coil is located above the red coil. Assuming the transmitting current flows from the red coil to the blue coil, the current in the red coil flows in a clockwise direction, and after passing through the blue coil, the current flows counterclockwise. The signal generated by the anomaly induces a current in the receiving coil in a clockwise direction. (b) shows the result after flipping the coils 180° . After the flip, the blue coil is now located below the red coil, and the current still flows from the red coil to the blue coil. In this case, the current in the red coil flows counterclockwise, which is consistent with the current direction in the blue coil in (a). After passing through the blue coil, the current flows clockwise, matching the current direction in the red coil in (a). This demonstrates that all the properties of the transmitted field remain unchanged before and after flipping the coils. However, since the transmitter and receiver coils are part of the same device, flipping the coil results in the receiver coil's direction reversing, which leads to the direction of the induced current in the receiver coil also reversing.

Equations (9) and (10) demonstrate that the measurement signals obtained using this forward and reverse coil flipping method differ from those obtained by conventional measurement techniques. This requires further discussion. We define the direction of the opposing coil's forward measurement as positive, with both the inductive signal and the geological body's response signal being positive. In this case, during forward measurement, the inductive signal and the geological response signal add together, and the measured signal is identical to that obtained by conventional methods, as shown by the green curve in Figure 3. When the coil is flipped, the relative strengths of the inductive and response signals must be compared. If $u_{ML} < u_{\tau}(t)$, flipping the coil causes the response signal to reverse its sign. When added to the inductive signal, the result remains negative, with the signal initially being the largest negative value upon shutoff, gradually decaying. This creates a signal with a distinctly different negative value from that in conventional measurements, as shown by the red curve in Figure 3. On the other hand, if $u_{ML} > u_{\tau}(t)$, the flip results in a reversal of the response signal's sign, but the magnitude of the response does not cancel out the inductive signal. In this case, while the flipped signal's strength decreases compared to the pre-flip signal, its overall shape remains similar, as shown by the blue curve in Figure 3. The signal behaviors hypothesized above are verified with experimental data in Section 3 of the manuscript, where two detection cases are presented. Therefore, by subtracting the two measurements, inductive interference can be eliminated, and the geological body's response signal is enhanced.

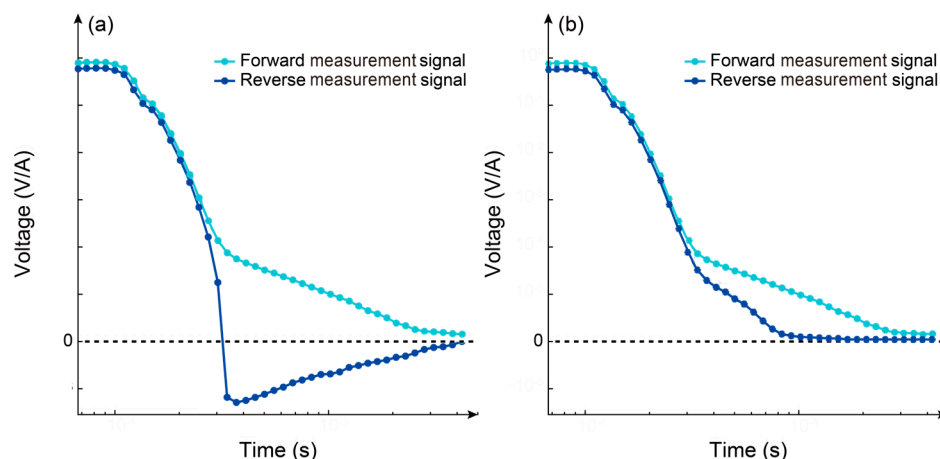


Figure 3. Typical Signal Characteristics for Forward and Reverse Measurements with Opposing Coils. (a) When $u_{ML} < u_{\tau}(t)$, the signal characteristics of the forward measurement and reverse measurement. (b) When $u_{ML} > u_{\tau}(t)$, the signal characteristics of the forward measurement and reverse measurement.

2.3. Calculation of Full-Field Apparent Resistivity of Opposing Coil TEM Field

The early signal of the small loop device is quite different from that of the traditional device, and one of the important reasons lies in the self-mutual inductance brought by the multi-turn coil. By the above method, we eliminate the influence of the self-mutual inductance of the coil. At the same time, the receiving coil and the transmitting coil of the opposing coil are coaxial, which achieves the best coupling with the abnormal body, so it has the characteristics of the same point device. Combining the above two points, we can treat the opposing coil signal as a “weakened” central loop signal, and the apparent resistivity can be calculated by the full-period apparent resistivity formula. Under the condition of uniform half space, the induced electromotive force at the center of the receiving coil is

$$\varepsilon(t) = \frac{SI_0\rho}{r_0^3} \left[3\varnothing(u) - \frac{2}{\sqrt{\pi}} e^{-u^2} u (3u + 2u^3) \right], \quad (11)$$

$$\varnothing(u) = \frac{2}{\sqrt{\pi}} \int_0^u e^{-x^2} dx, \quad (12)$$

$$u = \frac{r_0}{2} \sqrt{\frac{\mu}{\rho t}}, \quad (13)$$

In this context, I_0 is the excitation current, μ is the permeability of the medium, t is the observation time, r_0 is the radius of the transmitting coil, and $\varnothing(u)$ is the probability integral [29]. By normalizing Equation (9), the kernel function can be obtained.

$$f_{\varepsilon}(z) = \frac{1}{Z^2} \left[3\varnothing(z) - \frac{2}{\sqrt{\pi}} e^{-z^2} z (3z + 2z^3) \right], \quad (14)$$

Then, Equation (11) can be expressed as

$$\frac{4r_0 t}{\mu SI_0} \varepsilon(t) - f_{\varepsilon}(z) = 0, \quad (15)$$

where S is the effective area of the receiving coil, which leads to the following equation.

$$\rho = \frac{\mu r_0^2}{4\pi t} \frac{1}{z^2} \quad (16)$$

To solve Equation (15) and obtain the root z that satisfies the equation, it is then substituted into Equation (16) to compute the apparent resistivity value. The apparent resistivity over the full period, defined by the induced electromotive force, can be calculated using the bisection method. The normalized kernel function in the above equation is a double-valued function. The parameter z has zero points in the intervals $(0, 1.6)$ and $(1.6, \infty)$. Therefore, within these two ranges, the bisection method can be applied iteratively to approach the zero points, yielding the parameter z and providing an accurate solution for the apparent resistivity over the full period [30,31].

3. Results

Field measurements were conducted on both high-resistivity and low-resistivity targets. The electrical stratification of the site is detailed in Table 1.

Table 1. Electrical parameters of the experimental site.

Stratigraphic Name	Depth (m)	Resistivity ($\Omega \cdot m$)
Concrete pavement	0.3	>500
The filling	0.3~2.0	150~200
Undisturbed soil	2.0~12.5	<100
Bedrock (Jurassic red sandstone)	>12.5	About 200
Bellows cavity	1~1.45	$>1 \times 10^6$ (air)

3.1. Instrument Introduction and Measurement Parameters

The measurement system used in this experiment was the YCS360 TEM system (Made in China). The instrument parameters are as follows: The maximum output current is 5 A, with the transmitting current being a square wave with a 1:1 duty cycle. The transmitting frequency range is 2.5 Hz to 1000 Hz, and the shutoff time for a pure resistive circuit is less than 0.8 microseconds. The transmitter coil has a radius of 0.3 m with 50 turns, while the receiver coil has a radius of 0.3 m with 200 turns. The receiver's sensitivity and bandwidth are 10 kHz, with a maximum sampling rate of 1.25 MHz and a resolution of 1 microvolt. The system measures signal amplitudes from E0 to E6 with a dynamic range of 256 db. The measurement parameters were as follows: Transmitter coil: 50 turns. Receiver coil: 200 turns. Coil diameter: 600 mm. Transmitting frequency: 25 Hz. Stacking: 1024 stacks. Number of channels: 120 channels. Gain: Automatic gain control. Transmitting current waveform: Square wave with a duty cycle of 1:1. Observation time: On-time. Turn-off time: 36.8 μs .

The measurement procedure involved first recording the signal with the coil in its normal orientation (forward measurement), followed immediately by flipping the coil 180° and recording the signal again (reverse measurement) at the same location. Once both orientations were measured at a given point, the system moved to the next measurement point until the entire survey line was completed.

3.2. Field Experiment with a High-Resistivity Corrugated Pipe

Figure 4 presents a photograph and schematic diagram of the high-resistivity corrugated pipe. A drainage pipe with a diameter of 45 cm is buried approximately 1.2 m beneath the concrete pavement (Figure 4a). The location of the measurement points relative to the pipe is shown in Figure 4b. A survey line was laid out perpendicular to the pipe at the surface with a spacing of 0.4 m between each measurement point. The center of the pipe is located directly beneath measurement point 7. The results and analysis are as follows:

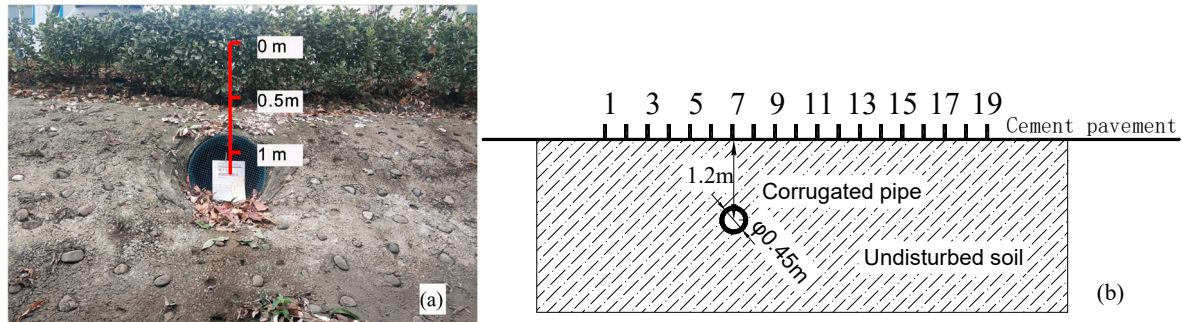


Figure 4. Pictures and model diagrams of the experimental site. (a) Drainage pipe in test site (b) Detection experimental diagram.

Figure 5 shows the induced voltage of 15 measurement channels for all 19 measurement points in the time period from 38.4 μs to 400 μs . From Figure 5, it can be seen that the voltage curves for the corresponding channels obtained using either forward measurement (Figure 5a) or reverse measurement (Figure 5b) are uniformly distributed without significant response differences. However, the voltage curves obtained after processing the signal difference (Figure 5c) show significant voltage variations. The potential at the measurement points over the target body significantly decreases, and the curves clearly reflect the target body (measurement points 6 to 8). Figure 6 shows the full-course voltage response curves for forward and reverse measurements at measurement points 1, 7, and 13. It can be seen that the inductance value of the opposing coil is small, and the voltage response curves after switching off are consistent with the characteristics shown in Figure 3b.

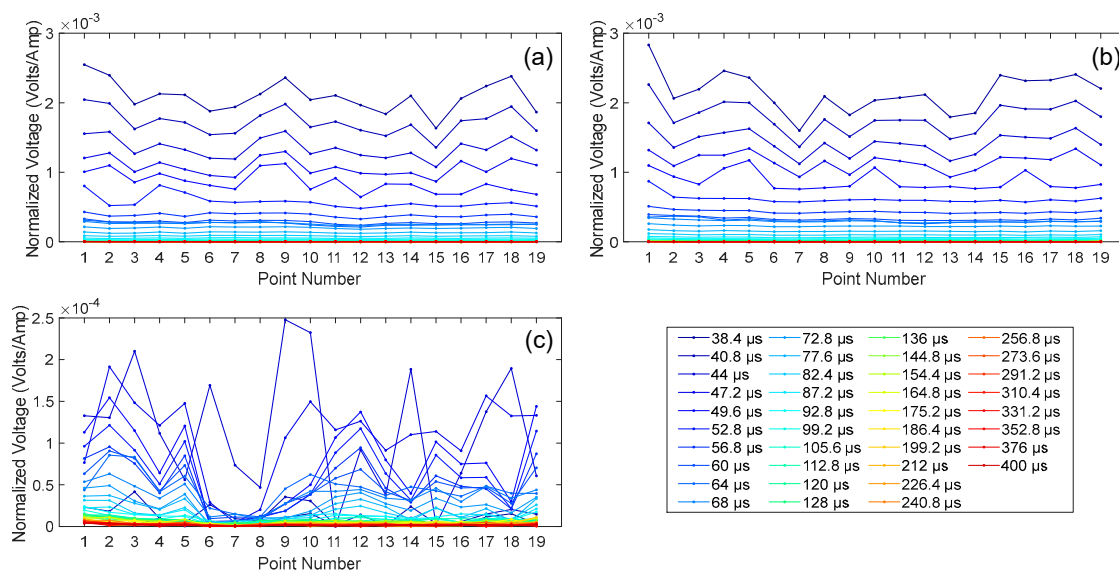


Figure 5. Measured corrugated pipe signals (38.4 μs –400 μs): (a) positive coil; (b) reverse coil; (c) positive-reverse difference.

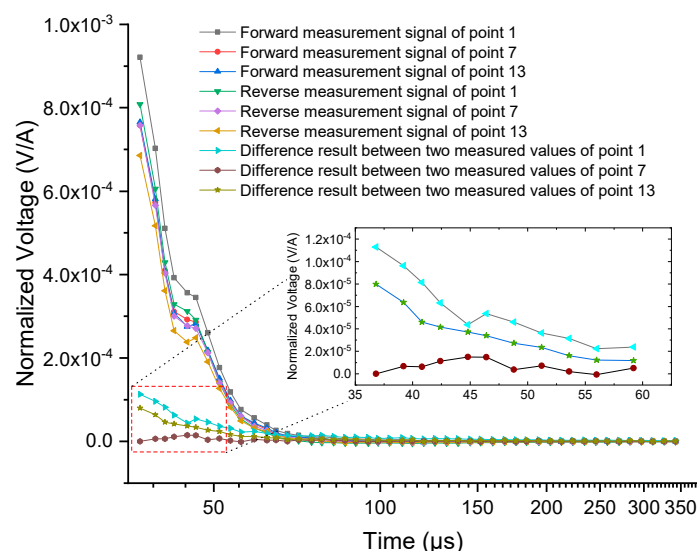


Figure 6. Full-Course Measurement Potential Curves for Points 1, 7, and 13 After Switch-Off.

Using the oblique step total-field apparent resistivity calculation method (in Section 2.3) for imaging, the apparent resistivity profile was obtained (Figure 7). As shown, the resistivity profiles for both the forward (Figure 7a) and reverse (Figure 7b) coil placements cannot distinguish the pipeline from the background. The main reason is the high resistance of the pipeline and its very shallow burial depth. However, after calculating the apparent resistivity from the difference between the forward and reverse measurement voltage signals (Figure 7c), a distinct circular high-resistance area is observed at a lateral distance of 2.3 m and a central depth of 1.5 m in the apparent resistivity profile. This area has an apparent resistivity greater than $750 \Omega \cdot \text{m}$, which corresponds to the actual location of the pipeline, verifying the effectiveness of this method.

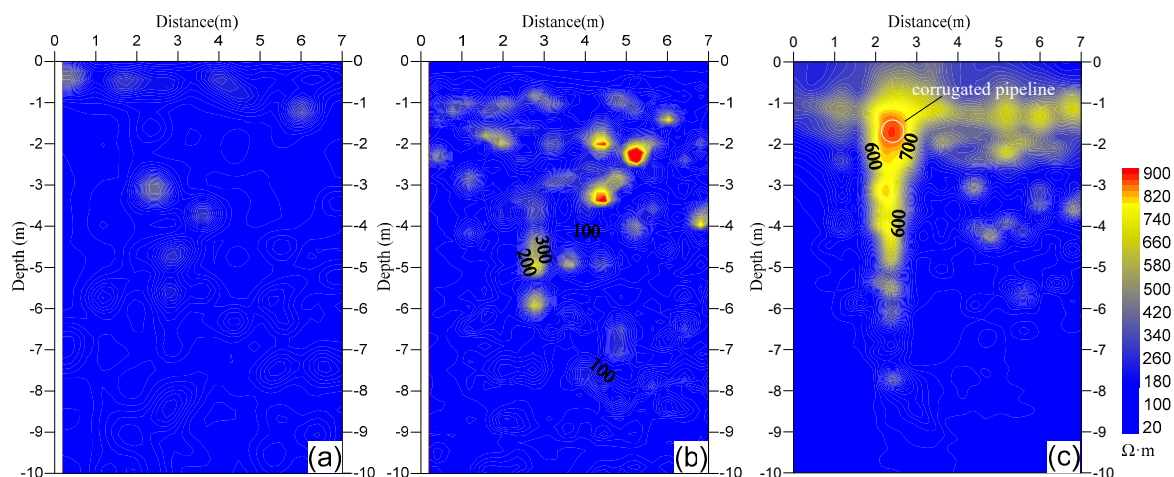


Figure 7. Apparent resistivity profile (a) positive coil signal; (b) positive coil signal; (c) difference between positive and reverse coil signals.

3.3. Field Test on Low-Resistance Gas Pipelines

In Section 3.1, we conducted a detection of the high-resistivity corrugated pipe and obtained excellent results. To compare the performance of this method for detecting low-resistivity geological bodies, we also conducted an additional experiment focused on detecting low-resistivity pipelines. It is known that there are two underground gas pipelines, with diameters of 711 mm and 219 mm, respectively. The pipelines are buried

at a depth of approximately 2.5 m, as shown in Figure 8. A survey line perpendicular to the direction of the pipelines was set up on the ground, with measurement points spaced 0.2 m apart. The pipelines are located at 0.4 m and 2.8 m positions along the survey line. The results and analysis are as follows:

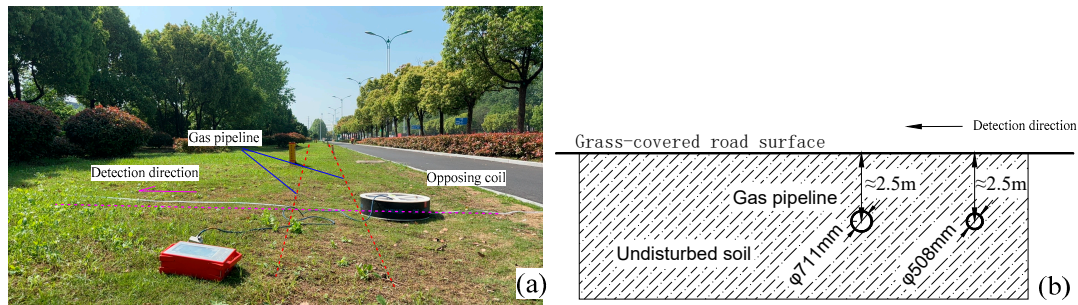


Figure 8. Field layout diagram of low-resistivity body detection experiments: (a) Photograph of the instruments and the field test site, with two red dashed lines indicating the known orientation of the underground gas pipeline. The detection direction is perpendicular to the pipeline's alignment. (b) Cross-sectional view showing the location of the low-resistivity anomaly within the detection area, with pipeline diameter and burial depth determined based on pipeline installation data.

Figure 9 shows the induced voltage of 19 measurement points, sampled between 75.6 μs and 371.28 μs . It can be seen that in the forward measurement signals, there are distinct high-potential characteristics at measurement points 3 and 15. In the reverse measurements, the high-potential locations are essentially consistent with those in the forward measurements. Due to the reverse reception of the receiving coil, the late-stage signals show significant negative values. After calculating the difference between the forward and reverse measurement signals, the high-potential positions remain unchanged, but the induced potential values are enhanced.

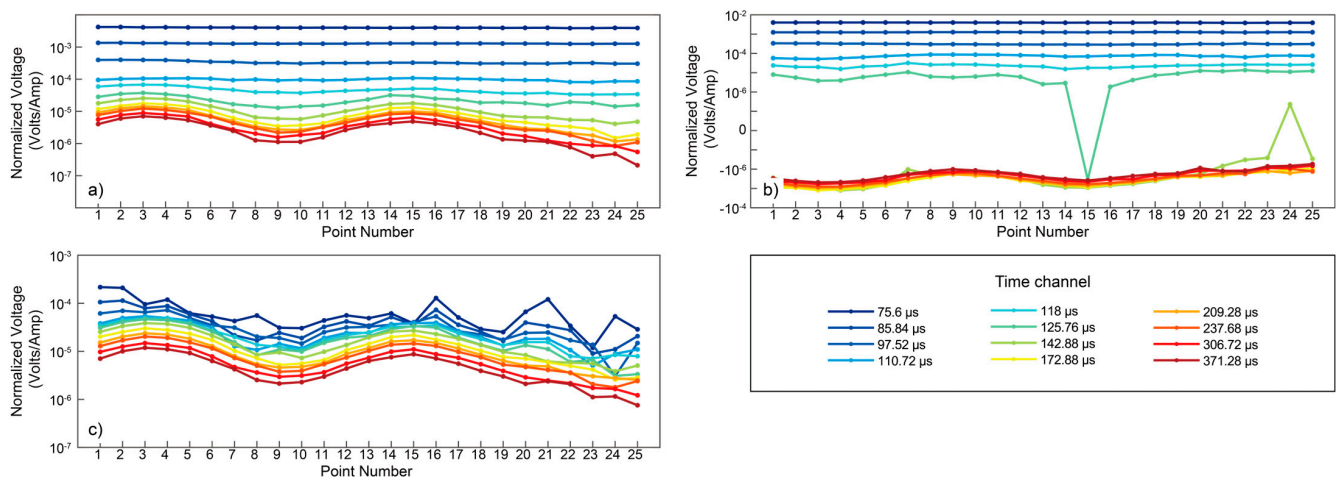


Figure 9. Measured gas pipeline signals (75.6–371.28): (a) positive coil; (b) reverse coil; (c) positive-reverse difference.

Figure 10 shows the full-duration voltage response curves from forward and reverse measurements at measurement points 3, 15, and 24. It is evident that the integrated signal from a single measurement before shutoff is significantly higher than the differenced signal up to 120 microseconds. Additionally, the reverse measurement signal exhibits negative values after 120 microseconds. The voltage response curve after shutoff is consistent with the characteristics shown in Figure 3a, indicating that the geological body's response signal is clearly stronger than the coil's inductive signal.

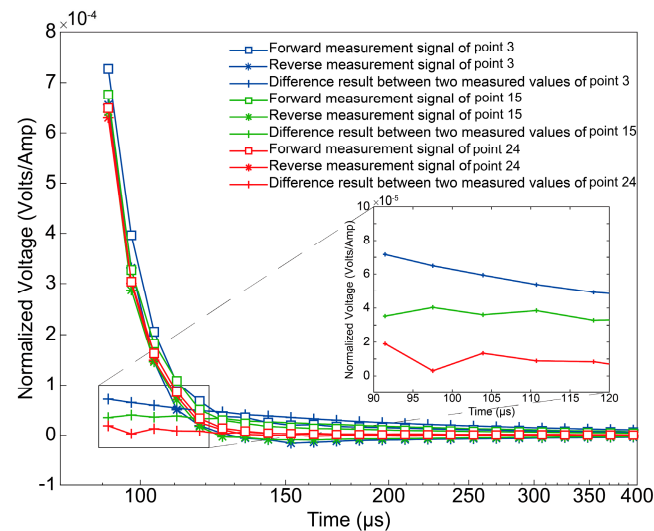


Figure 10. Full-Course Measurement Potential Curves for Points 3, 15, and 24 After Switch-Off.

Using the oblique step total-field apparent resistivity calculation method (in Section 2.3) for imaging, an apparent resistivity profile was obtained (Figure 11). As shown, when measured with the coil in the forward direction (Figure 11a), there are two distinct low-resistivity anomaly zones at positions 0.5 m and 2.8 m. The anomaly at 0.5 m is more pronounced, while the low-resistivity zone at 2.8 m is relatively smaller. When measured with the coil in the reverse direction, the results are similar to the forward measurements, but the response of the two low-resistivity zones is slightly lower than in the forward measurement. After taking the difference between the two, the apparent resistivity profile effectively reveals the positions and shapes of the two gas pipelines. The low-resistivity zone at 0.5 m has a lower resistivity and a larger range than that at 2.8 m, mainly because the gas pipeline at 0.5 m has a larger diameter. The detection results verify the effectiveness of this method.

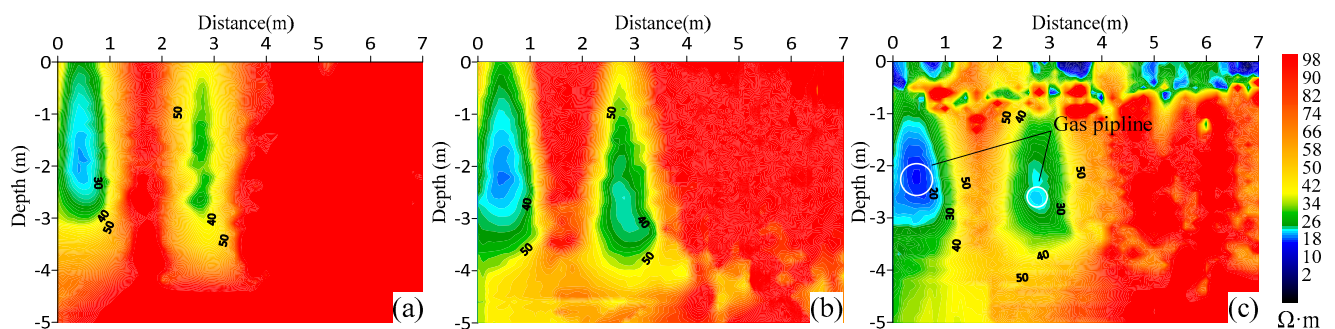


Figure 11. Resistivity Profile of the Gas Pipeline Survey. (a) positive coil signal; (b) positive coil signal (c) difference between positive and reverse coil signals.

4. Discussion

In this study, we used the opposing coil TEM method to perform two vertical flips of the measurement coil at the same measurement point, processing the voltage signal difference to eliminate the inductive signal between the multi-turn small-loop coils. Compared to the decoupling method, which adjusts the relative positioning of the transmitting and receiving coils, this approach theoretically eliminates the inductive effects between the two coils after current shutoff. Moreover, it does not require the receiving coil to be strictly placed on the zero magnetic flux plane between the two transmitting coils, thus reducing the technical difficulty in coil fabrication.

The key advantage of this method lies in the fact that the inductance between the transmitter and receiver coils is not affected by their absolute positions but only by their relative positions. As a result, the inductive signals before and after flipping the coils remain identical, and the properties of the transmitted field stay the same. Consequently, during the entire detection process, only the receiving coil's orientation changes, reversing the direction of the induced signal, which can then be removed by calculating the difference.

Figure 12 shows the raw signal graphs from the high-resistivity and low-resistivity detection experiments. The graphs in Figure 12 include raw signals from measurement point 7 in the high-resistivity experiment (a)–(c) and from measurement point 15 in the low-resistivity experiment (d)–(f). In the high-resistivity experiment, the underground medium around the high-resistivity pipeline is uniform, with no low-resistivity anomalies such as metals. The forward (Figure 12a) and reverse (Figure 12b) measurement signals show minimal differences, consistent with the expected response signal characteristics (Figure 3b). After performing differential calculations, the resulting signal (Figure 12c) shows a rapid decay after shutoff.

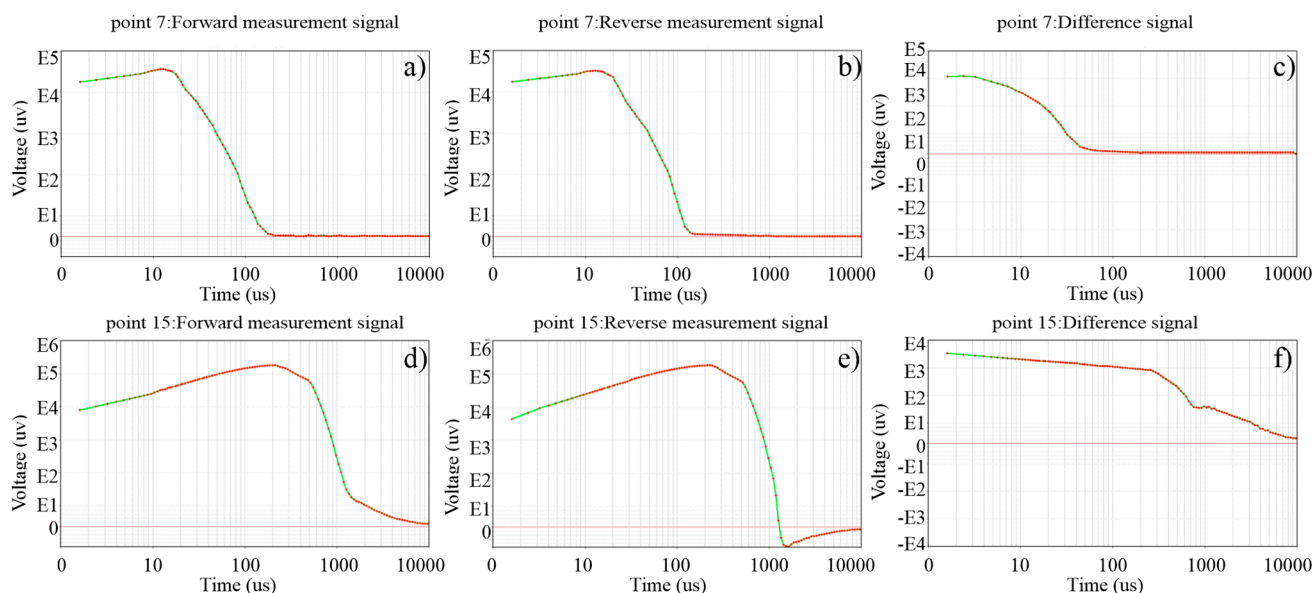


Figure 12. Raw time-voltage signal plots for measurement points 7 and 15 in high-resistivity and low-resistivity detection experiments: (a–c) raw signals for measurement point 7, (d–f) raw signals for measurement point 15.

In the metal pipeline detection experiment, the metal pipeline generates a prominent response signal (Figure 12d) that lasts for a relatively long time and has a large amplitude. During reverse measurements (Figure 12e), this strong response signal, which is opposite in sign to the forward measurement signal, becomes clearly visible as a negative signal after inductance disappears, consistent with the expected response signal characteristics (Figure 3a). After performing differential calculations, the resulting signal (Figure 12f) shows a very distinct response from the steel pipe, which remains observable throughout the entire sampling period after the current shutoff.

For the resistivity calculation of the signal after the difference processing, the physical experimental results in the manuscript are processed using the central loop signal, and the full-period apparent resistivity calculation formula is applied for imaging. The imaging results are generally consistent with the actual physical model. However, this processing approach is not specifically tailored for small-loop devices but rather is an approximate method based on the characteristics of the approach. It is not fully accurate, and further

discussion is needed on how to correct the resistivity and depth calculations for shallow TEM methods.

5. Conclusions

By performing differential calculations on the signals obtained from forward and reverse measurements using opposing coils, the self-induction and mutual induction signals caused by coil energization can be eliminated. This reduces the shallow detection blind zone and isolates the electromagnetic signal generated solely by the underground geological body. This signal is enhanced by the differential method, proving the principle's feasibility. Simulated detection experiments and actual field detection examples and verification results further confirm the method's effectiveness. The results demonstrate that the forward and reverse measurement method of opposing coils can reduce the TEM detection blind zone to within 1.5 m, significantly minimizing the shallow exploration blind zone of the TEM method and offering substantial application value.

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