Location and Characterization of Unexploded Ordnance-Like Targets With a Portable Transient Electromagnetic System

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ABSTRACT Location and characterization of a buried target from its electromagnetic induction response is a key problem for unexploded ordnance (UXO) detection. This article focuses on the influence of target size, depth, and orientation on its location and characterization on the basis of single dipole model with differential evolution (DE) algorithm against data collected by a portable transient electromagnetic (TEM) system. The sensor of the portable TEM system is composed of a single-layer transmitting coil and five three-component receiving coils. The diameter and current of transmitting coil are 0.5 m and 5 A. The length and resonant frequency of receiving coil are 5.6 cm and 180 kHz. The results of test-stand experiment show that the errors in location and characterization an underground target depend not only on the signal-to-noise ratio of the response, but also on the orientation of the target. For large target vertically (tail down) oriented, the estimated depth and characteristic response only represent the part of target close to the sensor, which are smaller than the real ones. For target flat-lying oriented, the algorithm overestimates both the depth and the characteristic response for the nonuniform primary field throughout the target. Finally, field experiment has been conducted. In general, the target can be located and characterized well even if the response of two targets is superimposed. The errors in estimated positions of about 5-7 cm support the conclusions from our test-stand experiment. These errors are especially critical when excavating targets.

INDEX TERMS Unexploded ordnance, electromagnetic induction, transient electromagnetic system, differential evolution algorithm, dipole model.

I. INTRODUCTION Unexploded ordnance (UXO) contamination has become a serious humanitarian and environmental problem worldwide, because it prevents land use by civilians, threatens public safety, and causes serious civilian casualties [1], [2]. In most cases, dangerous UXOs are mixed with a large number of harmless items such as miscellaneous shrapnel and metal. UXO problems are therefore ones concerned with discrimination between safe and dangerous targets rather than simple detection [3].

Geophysical exploration systems [4]–[6] such as magnetometry [7]–[9], electromagnetic induction (EMI) [10]–[12] system, and ground-penetrating radar [13]–[15] have been widely used to detect UXO. EMI sensing in both frequency and time domain, working in frequency range from approximately tens of Hz to hundreds of kHz, has proven to be successful in UXO detection. The transient electromagnetic (TEM) sensing has been found to be efficient in detecting and discriminating UXO. Newly developed TEM systems, such as the Oak Ridge Airborne Geophysical System [16], [17], the vehicle systems MetalMapper [18], [19], the Berkeley UXO discriminator [20], [21], the Time-Domain Electromagnetic Multisensor Towed Array Detection System [22], [23], and the portable systems [24]–[27] have been applied to detect and discriminate UXO-like targets efficiently. Because of their large size and weight, it is difficult to use vehicular systems in mountainous or jungle areas. In such areas, portable systems are preferred.

Detection, inversion, and classification are three stages in the UXO cleaning [28]. First, the ground needs to be inspected to determine whether a UXO-like target exists. The associate editor coordinating the review of this manuscript and approving it for publication was Zhixiong Peter Li.
All systems [16]–[27] have been developed to increase detection probability. Finally, detected targets need to be classified as UXO or clutter. Techniques such as maximum-likelihood methods, mixed models, support vector machines have been widely used [29]–[32] in this stage. Between detection and classification, the inversion recovers target’s position and electromagnetic characteristics on the basis of a physics-based model. Algorithms such as differential evolution (DE) algorithm [33], [34], HAP [35], and MUSIC [36], [37], are widely used in this stage.

For the simplicity, the single dipole model or some variation [38]–[42] has been the most current physical model in EMI sensing. However, the target in this model has been simplified to a point and the primary field throughout the target is considered uniform. Under realistic field conditions, the target has a certain volume, and distance between the sensor and different parts of target varies. All these will affect the accuracy in target location and characterization, which are also affected by instrumental and environmental noise. Thus, more attention should be payed to the errors of estimated position and characteristic response which come from the inaccuracy of the model when you are locating the target for excavation. Compared with the true position and calibrated characteristic response [43], [44], the article focuses on the influence of the target size (mainly refers to length), depth, and inclination on its position and characteristic response estimation is analyzed in test-stand experiments. Finally, the field experiments of 13 representative targets are conducted and discussed.

II. PORTABLE TRANSIENT ELECTROMAGNETIC SYSTEM

Figure 1 shows the electronic block and the picture of the portable TEM system. It can be seen in Figure 1 that the system is composed of a transmitter, a receiver, a controller, and a sensor. The first three parts are integrated into the portable instrument, and the sensor is connected to the instrument by a multi-core shielded cable for 15 responses and a twisted pair for transmitting current. The H-bridge of the transmitter, consisting of four N-channel MOSFETs, emits a bipolar trapezoidal pulse current in the transmitting coil at the frequency of 12.5 Hz. The resonant frequency of five three-component receiving coils is 180 kHz. The 15 channel responses were first amplified and then filtered to 60 kHz by the subsequent stage circuit. An ARM+FPGA dual-core architecture is used to control the entire system. A low-noise, high-speed octal 16-bit successive approximation register ADC with differential inputs has been chosen to acquire the target’s response and it can simultaneously sample eight channel signals at a 200 kHz sampling rate. Four PWMs are generated by the FPGA to generate the bipolar pulse waveform with a 50% duty cycle.

Figure 2 shows the physical and the equivalent models of the sensor.

As shown in Figure 2(a), the transmitting coil of the sensor is a single winding in order to reduce the distributed capacitance. Parameters $D$, $h$ are the diameter and height of the transmitting coil. The length of five receiving coils numbered from R1 to R5 is $a$. R3, located at $(0, 0)$, is in the center of the sensor. Other four receiving coils are located at R1$(0, d)$,
R₂(-d, 0), R₄(d, 0), and R₅(0, -d), where d is 20 cm. \( L_T \), \( r_T \), and \( C_T \) in Figure 2(b) are the inductance, resistance, and capacitance of the transmitting coil, respectively. For single-layer winding, the self-capacitance \( C_T \) of the transmitting coil is negligible. The five receiving coils are wound by a center tap; hence, \( L_1 = L_2 \), \( r_1 = r_2 \), and \( C_1 = C_2 \). Table 1 provides sensor parameters.

A 1.0 \( \Omega \) current-limiting resistor is connected in series to the transmitting coil. The transmitting current is measured by a GWINSTEK GDS-3502 digital oscilloscope (Good Will Instrument Co., Ltd., Taiwan, China). Figure 3 shows the measured results. As can be seen in Figure 3(a) that the amplitude and period of the transmitting current are 5 A and 80 ms. Figure 3(b) presents that switch-off time of transmitting current is approximately 40 \( \mu \text{s} \).

### III. DIPOLE MODEL AND RESPONSE INVERSION

Figure 4 presents the operation principle of TEM detection and dipole model of a target.

In Figure 4, the secondary field \( B_S \) of target excited by the primary field \( B_P \) at the position of receiving coil \( r \) is given by

\[
B_S = \left( \frac{3e_R e_R - 1}{4\pi R^3} \right) m = G(R)m, \tag{1}
\]

where \( R = r - r_d \), \( r_d \) is target position, \( e_R \) represents the unit vector along \( R \), \( R \) denotes the modulus of \( R \), \( I \) represents the identity matrix, and \( G(R) \) is the Green’s function. The dipole moment \( m \) can be calculated as follows:

\[
m = MB_P(r_d), \tag{2}
\]

where \( M \) is the magnetic polarizability tensor (MPT) of a target.

On the bases of Equations (1)–(2), the target response \( V \) for an EMI system can be calculated as:

\[
V = -G(R) \frac{dM}{dt} B_P(r_d). \tag{3}
\]

The characteristic matrix \( L(t) \) is defined as the negative derivative of \( M \).

\[
L(t) = -\frac{dM}{dt} = \begin{bmatrix}
L_{xx}(t) & L_{xy}(t) & L_{xz}(t) \\
L_{yx}(t) & L_{yy}(t) & L_{yz}(t) \\
L_{zx}(t) & L_{zy}(t) & L_{zz}(t)
\end{bmatrix} \tag{4}
\]

According to Equations (3)–(4), the target response \( V \) can be simplified as

\[
V = G(R)L(t)B_P(r_d). \tag{5}
\]

When detecting buried targets with TEM system, the target is excited by primary field generated from the transmitting coil at different positions. The response \( V_i \) picked up by five three-component receiving coils at the \( i \)th position can be recorded as

\[
V_i = \begin{bmatrix}
V_{i1} \\
\vdots \\
V_{i5}
\end{bmatrix} = \begin{bmatrix}
G_{i1} \\
\vdots \\
G_{i5}
\end{bmatrix} L(t)B_{P_i}, \tag{6}
\]

where \( B_{P_i} \) is the primary field in the target region at the \( i \)th excitation. \( V_{i1} \) to \( V_{i5} \) are 3 \times 1 dimensional vectors, which represent the responses recorded by the five three-component
receiving coils, respectively. $G_{ii}$ to $G_{ij}$ are the $3 \times 3$ matrix, which refers to Green’s functions of the five receiving coils, respectively.

To simplify the response inversion, the response of the buried target is decomposed into two parts: a nonlinear part consisting of only the target position $r_d$ and a linear part consisting of the target characteristic vector $p(t)$. We rewrote the Equation (6) as

$$ V_i = G_{ii} \begin{bmatrix} B_{Pix} & B_{Py} & B_{Pz} & 0 & 0 & 0 \\ 0 & B_{Px} & B_{Py} & B_{Pz} & 0 \\ 0 & 0 & B_{Px} & B_{Py} & B_{Pz} \end{bmatrix} p(t) = \gamma_i(r_d) p(t), \quad (7) $$

where $B_{Pix}$, $B_{Py}$, and $B_{Pz}$ are three components of the primary field $B_{Pi}$, $p(t)$ is a $6 \times 1$ dimensional vector whose components ($L_{xx}$, $L_{xy}$, $L_{xz}$, $L_{yy}$, $L_{yz}$, $L_{zz}$) correspond to the elements of the target characteristic matrix $L(t)$. $\gamma_i(r_d)$ is a $15 \times 6$ matrix, which is only dependent on the target position $r_d$.

The responses of the target excited by the primary field at $N$ different positions can be given by

$$ V = \begin{bmatrix} V_1 \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} \gamma_1(r_d) \\ \vdots \\ \gamma_N(r_d) \end{bmatrix} p(t) = \gamma(r_d) p(t), \quad (8) $$

where $V$ is a $15N \times 1$ dimensional vector and $\gamma(r_d)$ is a $15N \times 6$ matrix, which is only dependent on the target position $r_d$.

On the basis of the forward model $F(v)$ established by Equation (8), the model vector $v$, which includes target position $r_d$ and characteristic vector $p(t)$ of a buried object, can be estimated by least squares approach with the measured data $V_{obs}$ and the forward model $F(v)$ as:

$$ \min \phi(v) = \|V_{obs} - F(v)\|^2 = \|V_{obs} - \gamma(r_d) p(t)\|^2, \quad (9) $$

where $\phi(v)$ is the objective function, which quantifies the goodness-of-fit between forward model $F(v)$ and measured response $V_{obs}$. The inversion process is as follows.

First, the initial value of $r_{d0}$ is set to calculate $\gamma(r_{d0})$ based on Equations (7) and (8). The problem reduces to a linear system of equations which can be written as

$$ \gamma(r_{d0}) p(t) = V_{obs}. \quad (10) $$

Then, the solution to Equation (10) can be written symbolically as

$$ p_0(t) = \frac{\gamma(r_{d0}) V_{obs}}{\gamma(r_{d0})^T \gamma(r_{d0})}, \quad (11) $$

where $p_0(t)$ represents the best characteristic vector that corresponds to the target position $r_{d0}$.

The objective function $\phi(v_0)$ for the target position $r_{d0}$ and characteristic vector $p_0(t)$ can be calculated as

$$ \phi(v_0) = \|V_{obs} - \gamma(r_{d0}) p_0(t)\|^2. \quad (12) $$

Finally, the characteristic vector $p(t)$ can be estimated by optimizing the target position $r_d$. The global search procedure of the DE algorithm has been adopted to maximize the likelihood that the final solution is a global minimum not a local one. Optimized with the DE algorithm, the model vector $v$ can be finally estimated.

When the characteristic vector $p(t)$ is finally estimated, the target’s characteristic matrix $L(t)$ can be constructed based on Equation (4). With the singular value decomposition, the principal polarizability elements of the characteristic matrix $L(t)$ can be calculated as

$$ L(t) = U \begin{bmatrix} l_p(t) & 0 & 0 \\ 0 & l_{v1}(t) & 0 \\ 0 & 0 & l_{v2}(t) \end{bmatrix} U', \quad (13) $$

where $l_p(t)$ is the principal polarizability element parallel to the symmetry axis of the target, $l_{v1}(t)$, $l_{v2}(t)$ indicate the principal polarizability elements perpendicular to the symmetry axis of the target. For axisymmetric targets, $l_{v1}(t)$, $l_{v2}(t)$ are equal, and defined as $l_v(t)$.

The principal polarizability elements of the characteristic matrix $l_p(t)$, $l_{v1}(t)$, and $l_{v2}(t)$ are defined as the characteristic response $l(t)$ of a target to describe the electromagnetic characteristics of the target.

$$ l(t) = \begin{bmatrix} l_p(t) \\ l_{v1}(t) \\ l_{v2}(t) \end{bmatrix}, \quad (14) $$

In the next section, the location and characterization of targets under different conditions with a portable TEM system will be discussed in detail.

### IV. RESULTS

#### A. DESCRIPTION OF TARGETS

Table 2 and Figure 5 describe the 13 targets in the test-stand and field experiment.

In the following sections, the responses of all these targets are measured and inverted with the DE algorithm for target location and characterization in test-stand experiment and field experiment. Based on the early time response with high signal-to-noise ratio (SNR), the DE algorithm with 100 iterations is used to complete the inversion within 15 s.

#### B. TEST-STAND EXPERIMENT

1) TEST-STAND EXPERIMENT DESCRIPTION

Test-stand experiment is designed to measure accurately the response of the target under laboratory conditions with the

![Table 2. Parameters of UXOs.](image-url)
FIGURE 5. Thirteen representative targets used in our experiment. Targets U1 to U8 are dangerous UXO while targets O1 to O5 are safe metallic objects.

FIGURE 6. (a) Measurement grid for the test-stand experiment, (b) picture of the test-stand experiment.

FIGURE 7. (a) Targets at different depths, (b) targets with different dips, (c) targets of different sizes.

portable TEM system. The measurement is conducted for targets of different sizes at different depths with different orientations (symmetry axis of the target is set parallel the xoz plane). Figure 6 depicts the setup.

As shown in Figure 6(a), the measurement area is 80 cm × 80 cm, and the distance between the points is 20 cm. The sensor is fixed in the center of the area and placed upside-down on the ground, and the targets are moved around on the measurement grid above. For every target in different depths and dip angles, a total of 25 points with 375 responses are measured. The background response will be measured and subtracted from the total response to obtain a pure response of the target for data processing. Figure 6(b) is the picture of the test-stand experiment.

The influence of the target depth, dip angle, and size on its location and characterization is discussed in detail, as shown in Figure 7. The depth of a target is defined as the distance between the geometric center of the target and the ground in this study. Targets U1, U3, and U7 with tail up when vertically orientated are chosen for the convenience of analysis.

Figure 7(a) represents the six states when target U3 is placed at three depths of 30, 50, and 70 cm with two dips of 0° and 90°. Figure 7(b) represents the eight states when the target is placed at two depths of 30 and 60 cm with four dips of 0°, 30°, 60°, and 90°. Figure 7(c) represents the six states when targets U1, U3, and U7 are placed at depths of 50 cm with two dips of 0° and 90°. The measurement time in the test-stand experiment is from 0.1 ms to 10 ms. With 1 600 repetitions for a measurement duration of 64 s per data point, the SNR is greatly improved. All targets, namely, the 60, 82, and 100 mm mortar shells, will be located and characterized by the DE algorithm. The effect of the depth, dip, and size on target location and characterization will be discussed in detail.
2) INFLUENCE OF DEPTH, DIP, AND SIZE ON TARGET LOCATION

Figure 8 shows the inverted positions for targets in different depths, dips, and sizes. The results in Figure 8 show that the inverted positions fit well with the true positions in horizontal direction. However, the inverted depths are influenced by target depths, dips, and sizes. The inverted depth with a dip angle of 0° is obviously smaller than the true depth when the target is shallow and bulky, such as the 82 mm mortar shell at depth 30 cm or the 100 mm mortar shell. The inverted depth of the targets with a dip angle of 90° is greater than the true depth. The inverted depths of the small size target with the dip angles of both 0° and 90° agree well with the true depths, such as the 60 mm mortar shell.

![Figure 8: Influence of depth, dip, and size on target location.](image)

3) INFLUENCE OF DEPTH, DIP, AND SIZE ON TARGET CHARACTERIZATION

According to the single dipole model, characteristic response of a target does not change with the target depth, dip angle. However, the UXO has a certain volume, and the target length can usually reach tens of centimeters, which is comparable with the target depth. The characteristic responses

The influence of depth, dip, and size on target location can be explained in Figure 9. When a large target is close to the sensor with the dip angle $\theta = 0^\circ$, the distance between the head of the target and the sensor will be much smaller than the distance between the tail and the sensor, as shown in Figure 9(a). When detecting UXOs with EMI sensing, the response is inversely proportional to the 6th power of the distance [28] between target and sensor. The portion of target close to the sensor will account for a large proportion of the total response. Thus, the equivalent dipole will be closer to the sensor. The inverted depth $h_c$ will be shallower than the true depth $h_m$ in Figure 9(a).

In Figure 9(b), the target is placed with the dip angle $\theta = 90^\circ$. A, O, and C are the head, the center, and the tail of the target, respectively. The primary fields in these parts and the distances between these parts and the sensor are different. The target response can be equivalent to the superposition of three dipole responses at A, O, and C. The superposition of multiple dipole responses will make the response gradual with positional changing. Response of target close to the system will change violently with position, whereas the response becomes gradual. Thus, the target depth inverted based on a single dipole model will be greater than the actual depth of the target when the dip angle of target is $90^\circ$.

Under realistic field conditions, the location of an underground target is influenced not only by the noise but also by the orientation of the target. The one who locates the target for excavation should make a reasonable pre-judgment on the depth of underground target with the estimated position and orientation to reduce the risk of excavation as much as possible.

![Figure 9: (a) Location analysis when $\theta = 0^\circ$, (b) location analysis when $\theta = 90^\circ$.](image)
inverted based on the single dipole model varies with the depth, dip angle, and size of the target. Compared with the calibrated characteristic responses marked in blue and red, Figures 10 to 12 show the influence of depth, dip angle, and size on target characterization with very high SNR at early time.

Figure 10(a) shows that the inverted characteristic responses $I_p(t)$ at different depths fit well with the calibrated one when the dip angle $\theta = 0^\circ$, except one at the smallest depth of 30 cm, which is a bit smaller than the calibrated one. In Figure 10(b), the characteristic responses $I_p(t)$ and $I_v(t)$ inverted by the DE algorithm are highly consistent and greater than the calibrated ones at all depths when the dip angle $\theta = 90^\circ$. When a target with a dip angle of $0^\circ$ is close to the sensor, the head of the target will be much closer to the sensor than other parts, as shown in Figure 9(a). The response of the target head contributes the highest part of the entire response. The inverted characteristic response mainly represents the characteristic response of the target head, which is smaller than the real one.

As shown in Figure 11, the inverted characteristic responses $I_p(t)$ and $I_v(t)$ increase with the dip angle $\theta$ at the same depth. The difference between characteristic responses with different dip angles at a depth of 30 cm is much greater than the difference between characteristic responses at a depth of 60 cm. The target at a greater depth with smaller dip angle fits well with the calibrated one. When the dip angle of a target increases from $0^\circ$ to $90^\circ$ under the same depth, the distance between the target and the sensor tends to be consistent. The inverted characteristic response can accurately represent the characteristic response of the whole target. As the depth increases, the relative difference in
characterization. subtracted from the total response for target location and 0.06 ms to 20 ms. The ground response is measured and as 120 cm × 120 cm. The measurement time is from 0.06 ms to 20 ms. The ground response is measured and subtracted from the total response for target location and characterization.

2) MULTIPLE TARGETS INVERSION
The responses of twelve targets buried in 6 positions with 2 targets 40 cm apart have been measured and inverted. Due to the short distance, the responses of these targets over-
lap, introducing difficulties in separation. The DE algorithm has been improved to separate the response successfully. Figure 14 shows the results.

Figures 14(a) and (f) show that for the same targets, such as two 82 mm mortar shells and two 64 mm balls, the inverted characteristic responses $l_p(t)$ are highly consistent, verifying the reliability of the algorithm. In Figures 14(b), (c), (d), and (e), the inverted characteristic responses for the remaining eight targets have been effectively separated from each other. The characteristic response $l_p(t)$ for UXOs and harmless targets are all estimated with high SNR. Figure 14(d) shows that the inverted characteristic response $l_p(t)$ for harmless targets decay much faster, resulting in a difference in amplitude between two and three orders of magnitude within a few milliseconds. Table 4 shows the inverted positions of these targets.

In Table 4, the inverted positions for all targets fit well with the true positions. For UXOs with a dip angle of 0°, such as three 82 mm mortar shells numbered U3, the error of inverted horizontal positions is less than 3 cm, whereas the inverted depths are shallower than the true positions to 4–6 cm. For UXOs with the dip angle of 90°, such as U4, U5, U6, the inverted depths are deeper than the true positions to 5–6 cm. The errors of estimated position about 5-7 cm should attract more attention when one locates the target for excavation.

In general, targets can be well located and characterized even if the responses of multiple targets overlap.
V. CONCLUSION

With the structure and parameter of a portable TEM system for UXO detection described, the influence of target size, depth, and orientation on its location and characterization based on the single dipole model with DE algorithm is discussed in detail.

The sensor of the portable TEM system has been designed with one single-layer transmitting coil and five three-component receiving coils. The transmitting current has been limited to 5 A and the sample rate of the receiving system has been set as 200 kHz. All these designs make the portable system a high-performance instrument that provides a wealth of high-quality information.

By decomposing the target response into the product of the matrix that contains only the target position and the characteristic vector, the inversion has been turned into a process that consists of matrix calculation and characteristic vector estimation. The DE algorithm has been adopted to estimate the position and the characteristic response.

Compared with the true position and calibrated characteristic response, the influence of target depth, orientation, and size on target location and characterization is analyzed in detail by conducting a test-stand experiment. For targets with small size, the inverted depth agrees well with the true position, and the estimated characteristic response is also highly consistent with the calibrated one. For large targets, both the inverted depth and characteristic response are smaller than the real ones when vertically orientated and larger when horizontally orientated.

Finally, the responses of thirteen types of targets buried separately or two targets together have been measured in a field experiment. All these targets have been located and
characterized by the DE algorithm with very high SNR. The inverted results show that the proposed portable system combined with the DE algorithm can accurately locate and characterize the targets. The errors of estimated positions can reach 5 cm in horizontal direction and 7 cm in depth for separately buried targets or two targets close to each other, which verified conclusions again. The one who locates the target for excavation should pay more attention to these errors and make a reasonable pre-judgment on the scope for the excavation.

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