GEOPHYSICS, VOL. 69, NO. 3 (MAY-JUNE 2004); P. 664–673, 8 FIGS., 2 TABLES.
10.1190/1.1759452

Case History

Field tests of an experimental helicopter time-domain electromagnetic system for unexploded ordnance detection

Les P. Beard*, William E. Doll*, J. Scott Holladay‡, T. Jeffrey Gamey*,
James L.C. Lee‡, and David T. Bell*

ABSTRACT

Field trials of a low-flying time-domain helicopter electromagnetic system designed for detection of unexploded ordnance have yielded positive and encouraging results. The system is able to detect ordnance as small as 60-mm rounds at 1-m sensor height. We examined several transmitter and receiver configurations. Small loop receivers gave superior signal-to-noise ratios in comparison to larger receiver loops at low heights. Base frequencies of 90 Hz and 270 Hz were less affected than other base frequencies by noise produced by proximity to the helicopter and by vibration of the support structure. For small ordnance, a two-lobed, antisymmetric transmitter loop geometry produced a modest signal-to-noise enhancement compared with a large single rectangular loop, presumably because the antisymmetric transmitter produces smaller eddy currents in the helicopter body, thereby reducing this source of noise. In most cases, differencing of vertically offset receivers did not substantially improve signal-to-noise ratios at very low sensor altitudes. Signal attenuation from transmitter to target and from target to receiver causes signals from smaller ordnance to quickly become indistinguishable from geological background variations, so that above a sensor height of about 3 m only large ordnance items (e.g., bombs and large caliber artillery rounds) were consistently detected.

INTRODUCTION

Unexploded ordnance (UXO) on former military test ranges has been a major environmental concern as military bases have been scheduled for closure, cleanup, or redevelopment. By U.S. Department of Defense estimates, about 6 million ha (15 million acres), are UXO-contaminated at 1500 sites in the United States alone (Bowers and Bidwell, 1999). Geophysical surveys, primarily magnetic or electromagnetic (EM), play a key role in mapping ordnance locations for subsequent cleanup. For areas larger than a few hundred hectares, helicopter surveys can be an economical and time-efficient way to map ordnance provided the survey resolution parameters (the receiver spacing and height, and flight line spacing) are adequate for detection of the particular types of ordnance.

Since 1998, Oak Ridge National Laboratory (ORNL), Geosensors, Inc., and Airtech Canada have teamed to develop low-flying helicopter geophysical systems for UXO detection, initially with magnetometry, and more recently with transient EM and vertical magnetic gradient systems (Doll et al., 2001, 2003; Beard et al., 2003; Gamey et al., 2003). Unlike helicopter geophysical systems designed for mineral exploration, the ORNL systems use multiple sensors to collect data with a density comparable to that of a ground survey and, where survey conditions permit, fly at survey heights of 1–3 m above ground level. For example, the ORNL total magnetic field system has eight sensors spaced 1.7 m apart and can collect a 14-m wide swath of data in a single pass. Over areas of low vegetation and modest topography, typical survey altitudes average less than 2 m. The first helicopter EM sensor developed for UXO detection was a proof-of-concept system developed in cooperation with Geonics Ltd. This sensor, a two-receiver, single time-gate transient EM system based on EM-61 technology and described in detail in Doll et al. (2004), reliably detected medium to large ordnance in a field trial at the former Badlands Bombing Range (BBR) in South Dakota. Using the experience gained from work with the proof-of-concept system, a prototype system was subsequently developed with improved

Published on Geophysics Online February 6, 2004. Manuscript received by the Editor June 18, 2003; revised manuscript received December 8, 2003.
*Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37830-6038. E-mail: beardlp@ornl.gov; dollwe@ornl.gov; gameytj@ornl.gov; belldt@ornl.gov.
‡Geosensors, Inc., 66 Mann Avenue, Toronto, Ontario M4S 2Y3, Canada. E-mail: sholladay@sympatico.ca.

transmitter and receiver geometries, increased transmitter moment, programmable base frequencies, and multiple time gates.

In September 2002, we took the prototype EM system to the Badlands of South Dakota and flew it over an established test site at the former BBR where we have evaluated the performance of other airborne systems. The test site is seeded with ordnance and nonordnance items of various sizes and masses that are buried at representative depths to simulate a realistic range of responses. The goals of the test flights were to assess the prototype relative to the proof-of-concept sensor, to evaluate different configurations of the prototype over actual ordnance items, and to determine its limits of resolution. In this paper, we describe the results of several of these field tests.

SYSTEM DESCRIPTION

The Oak Ridge Airborne Geophysical System-Transient EM, or ORAGS-TEM, is designed to survey as low as 1–2 m above ground level. Although case histories of low sensor-height surveys with a towed bird have been described (Ferraccioli et al., 2002), our experiences with towed bird systems indicate that the pilot's view of the towed bird is impaired, making it difficult or impossible to sustain routine operation at sensor altitudes of less than about 10 m (Doll et al., 2000). Even if the sensors could be towed at heights of 1–2 m above ground, uncertainties in the orientation and position of the sensor bird would create difficulties in using the data for detection and mapping of small metal objects. Furthermore, a single sensor system would require an inordinate number of densely spaced survey lines, executed with unreasonably precise flying (Gamey and Mahler, 1999).

The ORAGS-TEM system (shown in Figure 1a) was designed for mounting on rigid Kevlar and carbon fiber booms attached to the underside of a Bell 206L Long Ranger helicopter. Rigid booms allow the helicopter to fly closer to the ground, thus increasing system resolution, and also permit precise control and assessment of receiver positions, thus allowing more accurate prediction of UXO locations. As currently configured, the helicopter system employs the transient EM method. As shown in Figure 1b, the transmitter coil may be arranged in a rectangular geometry or in a two-lobed configuration. In the rectangular transmitter configuration, an aluminum transmitter cable is wrapped four times around a 12 m × 3 m rectangular, composite frame. In the lobed configuration, two 3 m × 3 m transmitter coils are positioned along the outer portion of the booms with the center of the transmitter at 4.5 m from the helicopter center line. The weight of the booms, transmitter, and receivers is about 130 kg. For either configuration, the peak transmitter current is about 30 A. The turnoff time for the 12 m × 3 m rectangular transmitter is about 230 μs, and for the lobed configuration about 160 μs. For the ORAGS-TEM system, data is sampled at a rate of 10 800 Hz in the receivers during the transmitter off time, beginning 93 μs after the end of the transmitter turnoff ramp. At BBR, we tested two different receiver types: single-turn receiver loops having dimensions of about 2.7 m × 2.7 m, and also smaller coils. The small-coil receiver configuration consisted of two 23 cm × 60 cm multiple-turn loops vertically offset by 34 cm. This allowed us to make vertical gradient measurements as well as single-loop measurements. The small-loop receivers were mounted at the center of a crossbeam connecting the forward and aft booms, and the distance from the centerline of the helicopter to the receiver center was 4 m. Inputs from only two receivers could be recorded, so we opted for a gradient receiver configuration on the starboard side of the helicopter, and emplaced dummy receivers of equivalent shape and weight on the port side. A laser altimeter was mounted on the underside of the helicopter; positional information was gathered using differential GPS from a GPS receiver mounted inside the rear starboard boom.

The transmitter, receivers, and laser altimeter are integrated via a console containing a Pentium-3 computer, the transmitter power supply, the transmitter driver board, and a digital system control and acquisition board that governs all system timing and performs digitization for EM receiver coil outputs and auxiliary analog signals. The data from the acquisition board, from GPS positioning, and from altitude and attitude instrumentation are stored on a hard drive. These data can be quickly copied to an external drive for transport to a base computer for further processing and analysis.

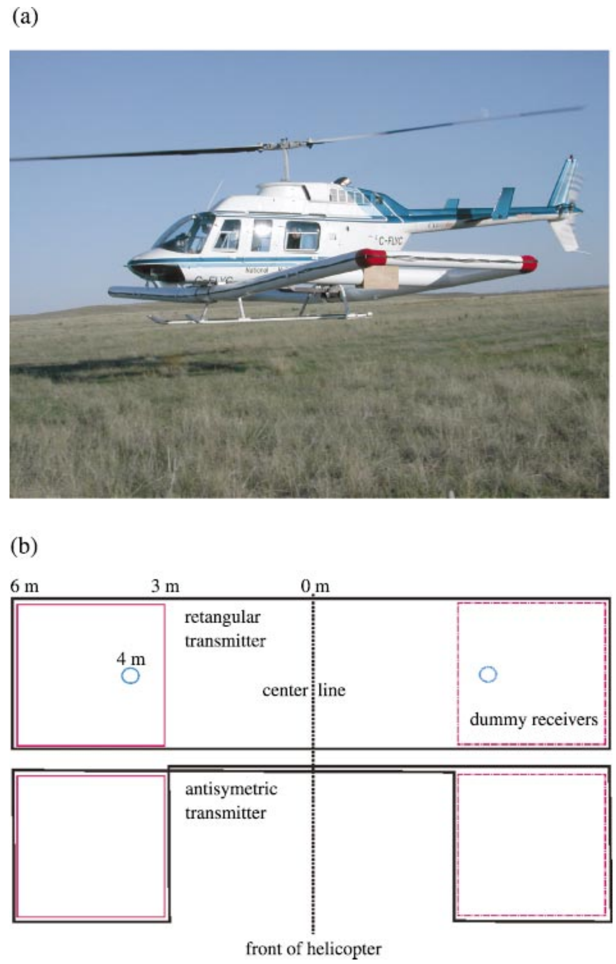

Figure 1. The ORAGS-EM system is designed for low-altitude surveying for unexploded ordnance. (a) In the configuration shown, the transmitter coil is wrapped in a rectangular 12 m × 3 m coil on the outside of the boom structure. Small coil-gradient receivers are mounted in the brown boxes on the crossbeams. (b) Diagrams of the different transmitter and receiver configurations. The red square shows the location of the large 3 m × 3 m loop receiver. The blue circles represent the small coil receivers.

TEST GRID

The test grid was constructed in an area of relatively flat rangeland on Cuny Table, a mesa bounded by steep escarpments bordering Badlands National Park in South Dakota. The soil is unconsolidated and thick, consisting mainly of layers of sand and silt. The geological background of the site is thus relatively clean, producing few sizeable short-wavelength EM anomalies that potentially could obscure ordnance anomalies.

Ordnance and nonordnance items were buried at a total of 53 different locations, distributed along eight rows spaced 15 m apart, in an area about 150 m × 105 m. Buried items were as small as 8-inch nails and as large as an inert, 250-pound bomb simulant. Along the rows, many items are evenly spaced 20 m apart, but some items are as close as 10 m and as far apart as 75 m. The buried items are more fully described in Table 1. Items are described as 100-lb or 250-lb bombs because that is their weight when filled with inert or explosive material. The actual amount of metal in the bomb is considerably less, and in some cases amounts to only a few kilograms. The accuracy of the locations of the buried items is generally good, but varies because the items were not all buried at the same time and the quality of GPS systems that were used to determine their locations was variable.

BBR FIELD TESTS

In this section, we focus on the subset of BBR field tests concerned with assessment of base frequency, transmitter and receiver geometry, and gradient measurements. Although we tried to make individual flights over the test area as equivalent as possible, differences in wind speed and direction, as well as variations in sensor positions and altitude, undoubtedly influenced measurements over individual ordnance items. However, by considering the test grid as a whole, or at least a significant portion of it, it is possible to make a reasonable assessment of the data collected by different transmitter-receiver configurations. The ORAGS-TEM system is a flexible framework for testing a wide variety of transmitter and receiver configurations and, as a result, it was expedient to use millivolts as a common unit for system output instead of units that would normalize changes in EM response resulting from different transmitter or receiver areas.

The test items were originally emplaced for the purpose of evaluating a helicopter-borne magnetic system for UXO detection (Doll et al., 2001) and, although background magnetic data were collected, no background EM data were collected because at the time a helicopter-borne EM system had not been planned. However, background geological heterogeneity is low, and we do not think the lack of EM background measurements detract from the results shown below.

In the sections that follow, the color scale on each grid has been allowed to vary in order to best display the test grid anomalies. The data as recorded comprised the EM response of target anomalies arising from isolated conductors in addition to response from conductive soil. The ground responses were strong enough to complicate gridding of the data, especially at early decay times. Fortunately, the target anomalies had distinctly shorter length scales than did the ground response anomalies. We therefore leveled the profile data before gridding by suppressing long-wavelength anomalies from the data, and thus extracted short wavelength anomalies related to compact sources. The long-wavelength suppression procedure is as follows. We first locate anomaly peaks along flight lines, default the values in the vicinity of the peaks, and interpolate across the gaps. That time series is then subjected to a low-pass filter to produce a smoothed estimate of the long-wavelength features. Finally, the low-passed time series is then subtracted from the original time series, yielding a cleaner anomaly pattern. This procedure proved highly effective for the Badlands data sets. As the final system design has not been established, we have not yet finalized our leveling procedures, and these are subject to change in the future. After final calibration and processing procedures have been established, we expect that conductivity mapping of soils should also be possible in addition to UXO detection.

In the final production system, attitude determination unit (ADU) sensors will provide information on helicopter pitch, roll, and yaw, but for these tests no ADU system was available. We thus had no way to correct for helicopter yaw, and this is reflected in some of the grids which show anomalies somewhat offset from the recorded receiver locations. This can amount to about 1 m for a yaw angle of 15°.

Transmitter base frequency and noise

A poorly chosen transmitter base frequency can defeat an otherwise well-designed transient EM system by creating a noise floor too high for detection of small ordnance. The primary sources of noise for a boom-mounted system are EM fields produced by the helicopter and vibration of the receivers. Shown in Figure 2 is a power spectrum computed for the first time sample (recorded 46 μs after turnoff) of the lower small-coil receiver during a high-altitude test flight. The transmitter used a 270-Hz base frequency. Noise spikes near 6.5 Hz and

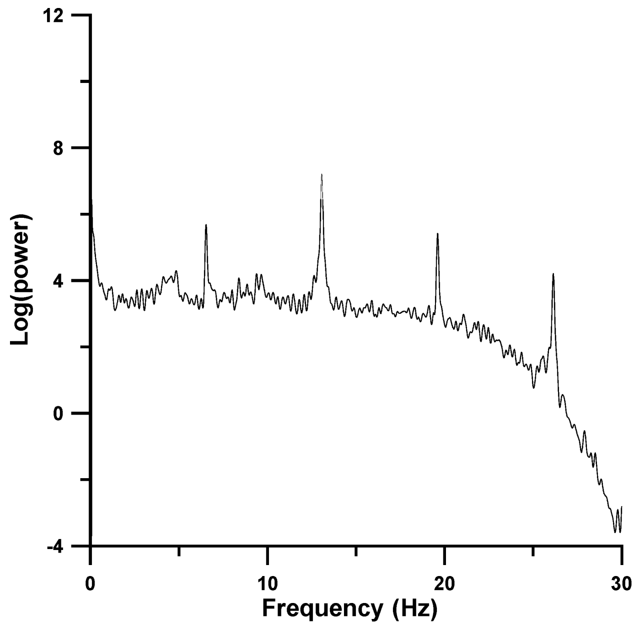

Figure 2. Power spectrum of small lower receiver during high-altitude flight with transmitter operating. Spectrum was computed with off-cycle data only from the first time window. Base frequency = 270 Hz. Survey speed = 20 m/s.

Table 1. Description of test grid items.

Item ID	Description	Weight (kg)	Long dimension (m)	Orientation	Depth of burial to top of item (m)
Row A					
A1	8-inch nail + 2-inch galvanized pipe	2.7	0.3	east-west	0.5
A2	3 rebar rods	5.5	0.8	random	0.6
A3	2-inch galvanized pipe elbow	4.5	0.6	random	0.7
A4	steel channel	6.8	0.5	random	0.6
A5	2-inch galvanized pipe	2.7	0.3	east-west	0.3
A6	2-inch galvanized pipe with flanges	4.5	0.4	east-west	0.4
A7	unknown				
A8	box beam	4.5	0.7	east-west	0.6
A9	galvanized stove pipe	1.8	0.8	east-west	1.0
A10	8-inch nail	0	0.2	vertical	0
Row B					
B1	I beam	13.2	0.4	east-west	0.4
B2	4 rebar rods	4.1	0.8	random	0.5
B3	I beam	4.5	0.2	random	0.6
B4	250-lb bomb	52	0.6	vertical	1.0
B5	100-lb bomb fragments	unknown	unknown	unknown	0.1
Row C					
C1	100-lb bomb fragments	8.6	unknown	unknown	0.4
C2	250-lb bomb simulant	22.7	1.6	north-south	1.3
C3	250-lb bomb simulant	29	1.6	east-west	0.7
C4	100-lb bomb intact	22.7	1.2	north-south	0.9
C5	100-lb bomb fragments	14.5	0.7	north-south	0.4
C6	2.75-inch rocket nose section	4.1	0.3	east-west	0.5
C7	155-mm round	24	0.6	vertical	0.7
C8	105-mm round	8.6	0.4	vertical	0.7
Row D					
D1	100-lb bomb fragments	unknown	unknown	random	0.1
D2	100-lb bomb fragments	unknown	unknown	random	0.1
D3	2.75-inch rocket cylinder	4.1	0.1	east-west	0.6
D4	2.75-inch rocket	2.3	0.7	north-south	0.6
D5	105-mm round	8.6	0.4	vertical	0.8
D6	2 2.75-inch rocket simulants	5.4	0.2	north-south and east-west	0.4
D7	61-mm mortar round	0.9	0.2	vertical	0.4
D8	105-mm round	8.6	0.4	vertical	0.8
Row E					
E1	81-mm round	4.1	0.4	vertical	0.4
E2	aluminum rod	0.5	0.9	east-west	0.3
E3	aluminum rod	0.5	0.9	east-west	0.5
E4	aluminum rod	0.5	0.9	east-west	0.8
E5	81-mm round	3.6	0.4	north-south	0.7
E6	81-mm round	3.6	0.4	north-south	0.8
E7	105-mm round	8.2	0.4	east-west	0.3
Row F					
F1	81-mm round	3.2	0.4	north-south	0.6
F2	60-mm illumination round	1.8	0.4	east-west	0.1
F3	60-mm illumination round	1.8	0.4	north-south	0.1
F4	60-mm illumination round	0.9	0.4	vertical	0.1
Row G					
G1	81-mm round	3.2	0.4	east-west	0.5
G2	100-lb bomb	2.7	0.8	vertical	0.5
G3	60-mm mortar round	1.4	0.2	vertical	0.4
G4	2.25-inch rocket	4.5	0.7	north-south	0.5
G5	steel pipe	4.1	0.5	east-west	0.6
Row H					
H1	8-inch nail	0	0.2	vertical	0
H2	2.75-inch rocket	3.2	0.3	north-south	0.9
H3	155-mm round	25.5	0.5	east-west	0.9
H4	155-mm round	25.5	0.6	north-south	0.7
H5	155-mm round	25.5	0.6	vetical	0.6
H6	8-inch nail	0	0.2	vertical	0

13 Hz are related to EM noise produced by the helicopter rotor and blades, respectively. The 13-Hz peak and higher frequency peaks can easily be removed during processing without attenuating UXO anomalies. Broad noise peaks can be problematic when they occur within the portion of the spectrum where the signal occurs. In our case, the broad 4.5-Hz noise peak, most likely caused by oscillation of the boom assembly, overlaps some UXO anomalies at suitable flight speeds. We therefore used base frequencies that produced few and small low-frequency spectral peaks.

Aside from noise concerns, a base frequency chosen too high may provide insufficient decay duration between transmitter cycles for ordnance discrimination, whereas a base frequency chosen too low can stack too few times over a target and thus fail to resolve the anomaly peak. We evaluated system performance at different base frequencies by flying over a line of targets using a selection of base frequencies, and also by collecting high-altitude receiver noise with and without transmitted signal. Upon computing noise spectra, we found that at typical survey speeds, base frequencies of 270 Hz and 90 Hz produced the highest signal-to-noise ratio (SNR). A base frequency of 270 Hz typically yielded a higher SNR than did 90 Hz, although 90 Hz yielded more useful information on the transient decay characteristics of the targets. While a 90-Hz base frequency was used in several tests at BBR, we used 270 Hz in all tests, and in particular for comparison of different transmitter-receiver configurations.

Receiver type and geometry

On shakedown flights prior to the BBR tests described in this paper, the small coils had been mounted directly on the leading boom. Noise levels from this configuration were deemed unacceptable, especially under high wind conditions (Beard et al., 2002). We hypothesized that larger loops should yield lower noise as they would be less affected by boom vibration. We also wanted to evaluate different positions for the small coils that had shown reduced noise levels in on-ground tests.

We examined two types of receivers. In one arrangement, two small multiple-turn coils measuring 23 cm × 60 cm were mounted halfway along a crossbeam connecting the forward and rear transmitter booms, and located 4 m from the helicopter centerline. The coils were vertically offset by 34 cm to provide vertical gradient measurements as well as single-coil measurements. The second receiver arrangement consisted of two 2.7 m × 2.7 m single-turn loops affixed to the top and bottom of the outer part of the boom assembly and crossbeam, and centered 4.5 m from the centerline of the helicopter. The vertical offset between the two large loops was 30 cm.

Figure 3 shows a grid from data collected at a nominal sensor height of 1 m with a base frequency of 270 Hz using small-loop receivers. Also shown in the figure are locations of the buried items. Because there was only a single pair of small-loop receivers in the experimental system, the lines were unevenly spaced over the test grid. Flight lines were more densely spaced over the lines of targets than in between, and the gridding of the data reflects this irregular line spacing. Anomalies over the test grid are plotted for the first time sample of the lowermost receiver coil. All ordnance items produced detectable responses, the largest being from the 250-lb and 100-lb bombs and bomb simulants. The only nonordnance items that did not show a response in the gridded data was a steel pipe over which the receivers did not pass using this configuration, (item G5) and an aluminum rod (item E3).

Figure 4 shows data collected over the same area using the large-loop receiver. Given that the helicopter did not fly exactly the same paths, the results are comparable. Nonordnance items that were missed are two sets of rebar rods and the most deeply buried aluminum rod (E4). Both small and large receiver types detected ordnance as small as 60-mm illumination rounds. Over ordnance, the peak amplitude of the small-coil receiver was generally larger than that of the large loop. For both receiver types, noise levels appear acceptably low. For the small-coil receivers, the use of vibration-isolators in the receiver assembly played a key role in noise reduction. At low altitudes, the SNR was a factor of two to ten times higher for the vibration-isolated small coils than for the large loops, as can be seen from the examples in Table 2, which shows the best signal-to-noise estimates for the various classes of ordnance.

Gradient versus single-coil receivers

We tested vertical gradient receivers as a straightforward way to increase the SNR. If the noise at the upper and lower receiver coils is sufficiently well correlated, the SNR will increase over that measured from a single coil despite the fact that the differencing operation also reduces the size of the anomaly. Both large- and small-loop receivers were arranged for vertical gradient measurements. The large-loop receivers were affixed

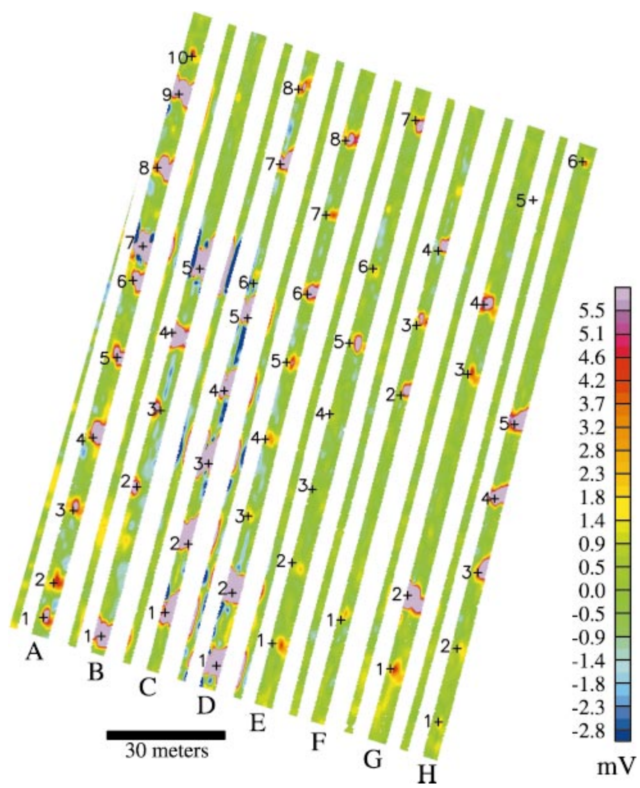

Figure 3. Response of first time gate of small lower receiver coil using rectangular loop configuration, 270-Hz base frequency, and nominal sensor height of 1 m above ground level. White stripes indicate areas where no data were collected.

to the top and bottom of the outer portion of the boom assembly. For the purposes of these tests, gradient measurements were obtained by measuring the off-time response at each of the two receiver coils, then subtracting the response of the upper coil from that of the lower one. While this approach does not yield the signal-to-noise and dynamic range benefits that could be obtained through the use of a pair of matched receiver coils connected in opposition, it did permit a preliminary investigation of the gradient approach without sacrificing acquisition of the individual responses at each coil. Figure 5 shows small-coil vertical-gradient results computed with data from the same flight at 1-m sensor height shown in Figure 3. For many items, the gradient anomalies are equally apparent over background as those from the single coil. In our test, any anomaly that

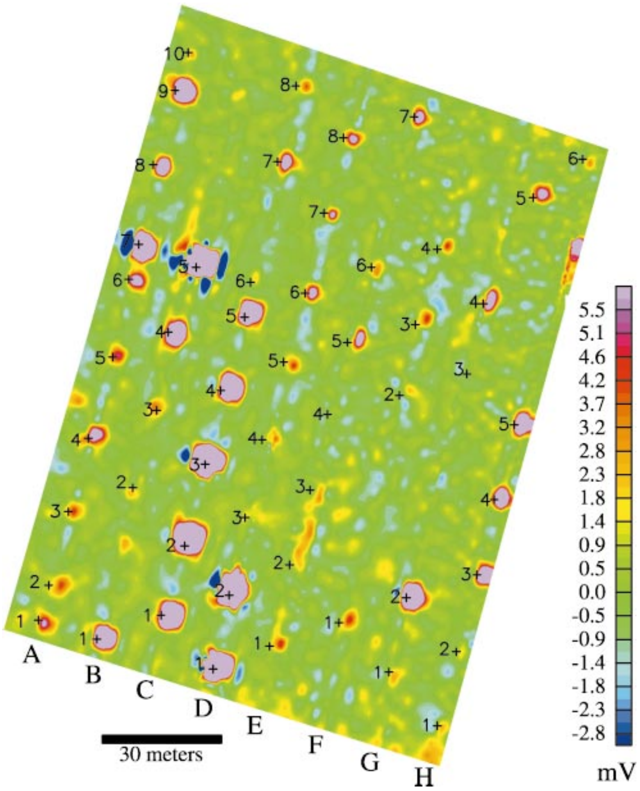

Figure 4. Response of first time gate of 3 m × 3 m lower receiver coil using rectangular loop configuration, 270-Hz base frequency, and nominal sensor height of 1 m above ground level.

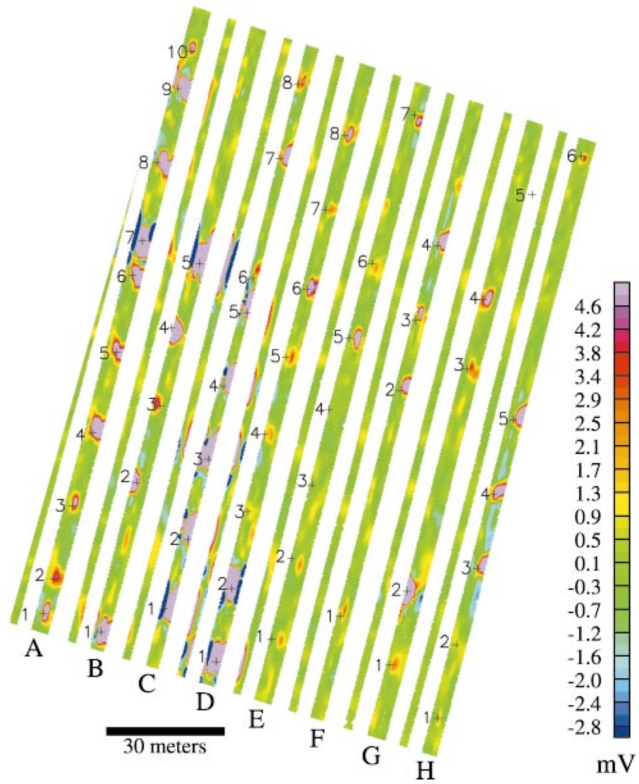

Figure 5. Vertical-gradient response from small-loop receivers, first time gate, 270-Hz base frequency, 1-m nominal sensor height. White stripes indicate areas where no data were collected.

Table 2. Peak-to-peak signal-to-noise estimates for selected ordnance.

Ordnance	Small receiver coils	Small receivers—vertical gradient	Large-loop receivers	Large-loop receivers—vertical gradient	Large-loop receivers—lobed transmitter
1.5-m nominal sensor-target separation					
250-lb bomb	2963	2107	289	631	326
100-lb bomb	1086	395	142	267	95
155-mm shell	128	99	40	33	24
105-mm shell	83	29	16	24	10
2.75-inch rocket	22	11	13	21	13
81-mm shell	23	21	9	0	11
61-mm shell	23	0	7	11	0
4-m nominal sensor-target separation					
250-lb bomb	22	1	20	3	31
100-lb bomb	8	0	6	5	9
155-mm shell	80	0	1	1	1
105-mm shell	80	0	0	0	1
2.75-inch rocket	80	0	0	0	2
81-mm shell	80	0	0	0	0
61-mm shell	80	0	0	0	0

appeared in the small-coil gradient data also appeared in the small-coil lower sensor data. Two 2.75-inch rockets (items D3 and H2) do not show gradient anomalies and, in addition to the non-UXO items missed by the lower coil alone, an additional aluminum rod and an 8-inch corner nail do not appear in the vertical gradient data. In the profile of line C (Figure 6), the vertical-gradient response computed from the first time sample of the upper and lower coils compares favorably with the response of the first time sample of the lower coil alone, except for item C8, a 105-mm round buried to a depth of 0.7 m. This is in keeping with the expectation that vertical gradient response falls off faster with sensor-target distance than does single-loop response. Our calculations indicate that at heights below about 1.5 m, SNRs from data using the small-coil vertical-gradient configuration are the same or slightly lower than the lower coil response alone, and that at higher altitudes the gradient SNR is significantly lower than that of the single coil. This is evident in examining the second half of Table 2, which shows that at sensor heights of 3 m, even the largest ordnance produced a poor SNR in gradient configurations. Although results are not displayed in grid form, Table 2 shows that the large-loop gradient SNR was the same or modestly higher than the lower large-loop SNR for most ordnance at the lowest survey height.

Transmitter loop geometry

In most of the BBR field tests we used a 12 m × 3 m rectangular, four-turn transmitter loop that produced a moment of about 5000 $A \cdot m^2$. This configuration is relatively easy to install and gave satisfactory results, but the zone of maximum transmitted field for this geometry runs directly beneath the helicopter, resulting in a strong secondary field arising from the helicopter body. We tested an anti-symmetric, 3 m × 3 m, double-lobed transmitter configuration (sketched in Figure 1b) in combination with large-loop receivers. We hypothesized that the two transmitter loops, having opposite polarities, would produce fields that would tend to cancel one another in the vicinity of the helicopter body, producing less eddy current noise from the helicopter frame and components. The two-lobed variant had a total moment of about 2500 $A \cdot m^2$ and produced transmitted field maxima on either side of the helicopter, closer to the receiver positions. Time limitations precluded flying the entire test area with this configuration, and results are mixed. The antisymmetric lobed transmitter produced modest increases in SNR with some targets in comparison to the large rectangular transmitter/large-loop receiver configuration, but was the same or smaller for other targets, as can be seen in Table 2. The dual transmitter loops may hold an advantage for higher altitude surveys. Figure 7 shows that some of the targets appear sharper with the antisymmetric lobed configuration than with the large rectangular loop transmitter.

Decrease in signal strength with altitude

One of the most difficult problems to overcome in designing an active source airborne EM system is the steep UXO signal decay with increasing altitude. The decay from an active source system takes place from transmitter to target, and again from target to receiver. As noted by Nabighian and Macnae (1991),

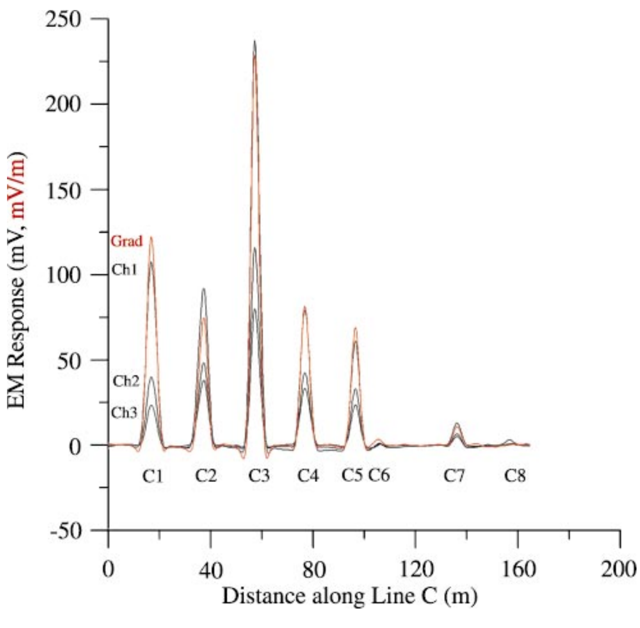

Figure 6. Responses from first three time gates (shown in black) of small lower receiver coil using rectangular loop configuration, 270-Hz base frequency, and nominal sensor height of 1 m above ground level. Red dashed curve is the vertical gradient computed for the first time gate of the upper and lower receiver coils. Numbers above anomalies represent the eight different items along line C (see Table 1).

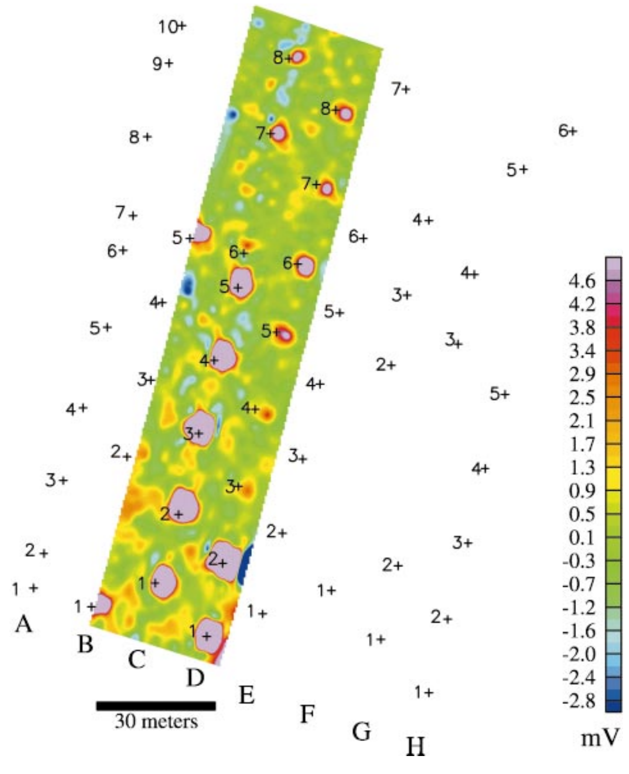

Figure 7. Increased resolution over targets using double lobed transmitter configuration shown in Figure 1b. Response of first time gate of large lower receiver coil, lobed transmitter configuration, 270-Hz base frequency, and nominal sensor height of 1 m above ground level. Only about one-third of the test area was flown with this transmitter-receiver configuration.

for small geologic targets, transient EM systems exhibit a SNR that can be approximated by $(R_n/R_t)^m$ where R_n and R_t are distances from the receiver to the source of geologic noise and the target, respectively. For large loops, $m = 4$; for small loops, $m = 6$. Our low-flying system, with its 12 m × 3 m transmitter loop, exhibits characteristics of both large loop and small loop-systems, depending on the position and size of the particular ordnance item. We thus expect the SNR exponent m will have values over the entire spectrum from 4 to 6.

Figure 8a shows a map of the EM response for the large-loop receiver system at 2-m nominal sensor height. At this height, clear ordnance-related anomalies are produced by all of the M-38 practice bombs and 250-lb bombs, as well as the 155-mm shells. Ordnance items smaller than 155-mm rounds generally did not produce anomalies, an exception being a 105-mm shell (item E7).

Figure 8b shows a map of the EM response for the large-loop receiver system at a 3-m nominal sensor height. At this height, the response of most of the small ordnance has fallen below the noise threshold, and only the M38 practice bombs and 250-lb bombs produce clear anomalies, although other items produced a few small anomalies still detectable in gridded data from non-UXO and even a few UXO items. Items C7, H3, and H4 are 155-mm rounds that show anomalies. Curiously, two items appear in the 3-m grid that do not appear in the 2-m grid. Small but distinct anomalies are located near item E5, an 81-mm shell, and item H2, a 2.75-inch rocket. The magnitudes of their anomalies at 1-m survey height are about 10 mV and 2 mV, respectively, so even with a conservative R^{-4} decay, at 3 m the anomalies should be in the noise, so their sources may be other than buried UXO. Aircraft roll appears to be more of a factor at higher altitudes than low because the pilot has a greater tendency to maneuver, and this can produce small anomalies even where ordnance is not present.

DISCUSSION

Achieving signal-to-noise improvement in the boom-mounted helicopter EM system has been an incremental process of identifying and reducing the sources of noise in different parts of the system. Some key factors in noise reduction were finding the best locations for the receivers, finding the most appropriate base frequencies, improving console electronics, employing vibration controls, and determining the best transmitter and receiver configurations for UXO detection. Under good field conditions (i.e., low wind and level terrain that allows a low sensor height), the ORAGS-TEM system in its present form is capable of reliably detecting ordnance items as small as 81-mm and 60-mm rounds, equivalent to the current detection limits of boom-mounted helicopter magnetic systems.

Our best helicopter EM results approach those of ground-based transient EM systems (Doll et al., 2003). Our experience with helicopter magnetic data at UXO-contaminated sites indicates that we can usually predict the location of a buried ordnance item to within a 1.5 m radius, even though the magnetic anomaly produced by the UXO may be several meters wide, because the peak of the anomaly usually lies directly above the ordnance item. We anticipate similarly accurate results with time-domain EM once we have implemented multiple receivers and have installed an ADU system to control roll, pitch, and yaw variations.

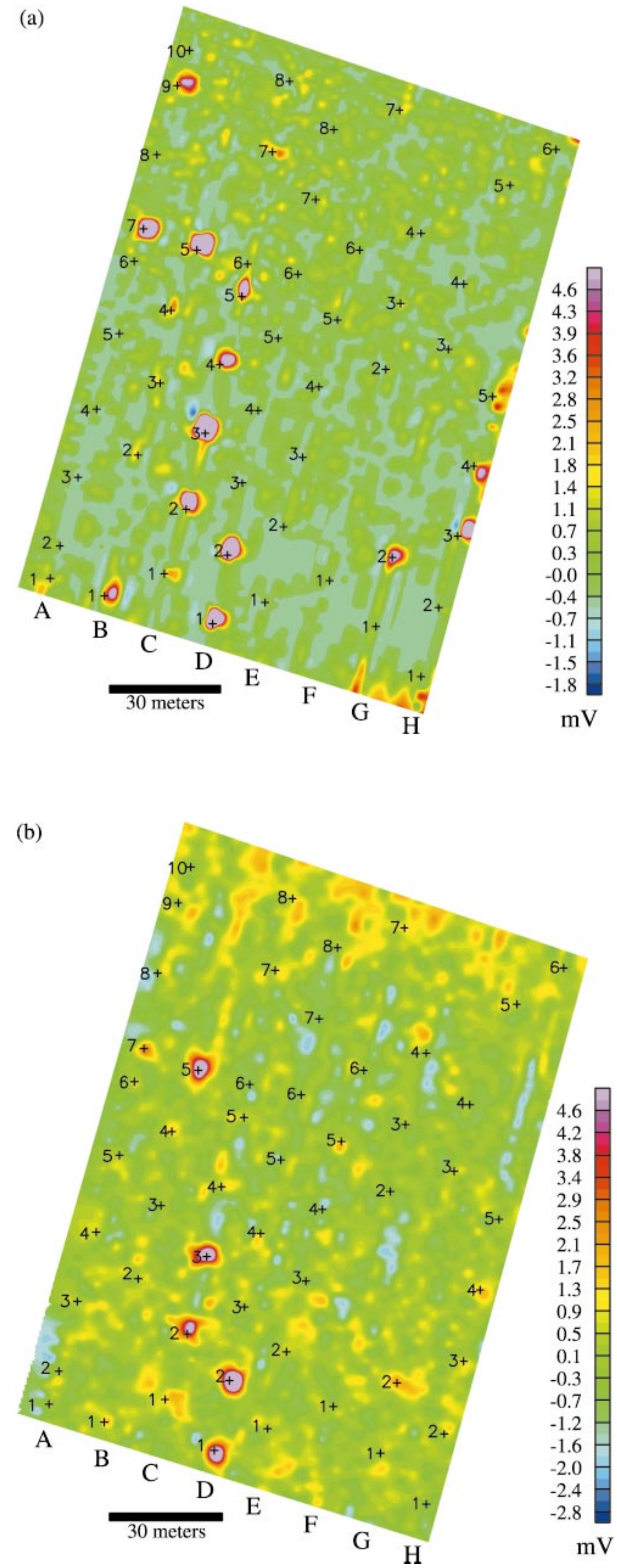

Figure 8. Response of first time gate of large lower receiver coil using rectangular loop configuration, 270-Hz base frequency: (a) nominal sensor height of 2 m above ground level, (b) nominal sensor height of 3 m above ground level.

The use of small-coil vertical-gradient receivers did not appreciably enhance SNR at low altitudes. Any object detectable with vertical-gradient measurements was also detectable in lower receiver data alone. However, gradient measurements are less affected than single-coil data by helicopter interference, sensor drift, and geological effects, and therefore the data can be used directly without resort to leveling. If the SNR of the gradient configuration can be improved, this would be a distinct advantage. We believe that the different sensor-to-target signal decay rates in single-loop measurements and gradient measurements imply that gradient data could be used for depth discrimination. For a particular ordnance item, if an anomaly appears in single-coil measurements but not in the vertical-gradient measurement, its causative source would likely be more deeply buried than if anomalies appeared in both data sets.

The importance of low sensor height for detection of small ordnance items cannot be overemphasized. For example, the EM response of an ordnance item at the surface of the earth measured at a sensor height of 1-m above ground may decrease by more than 50% with a 15-cm altitude increase. Although Gamey et al. (2003) have demonstrated that with magnetic gradient measurements it is possible to detect ordnance at heights of 7 m above ground, it seems unlikely that active-source EM systems will attain similar sensitivity at altitude. Vertical magnetic-gradient systems succeed largely because they eliminate a large component of helicopter noise. This noise reduction is more difficult to achieve with EM. EM fields produced by the helicopter vary more over short distances than do magnetic fields, and are more difficult to eliminate using differencing in the range of parameters in which the system operates. For the present, it appears that the most effective use of multiple receivers in a future system would be to mount several small receivers laterally so that a wider swath of ground can be investigated during a single pass of the helicopter. A final multisensor EM system will probably take the form of six to eight laterally separated sensors.

The data shown in this paper were leveled by removing long-wavelength features. Only anomalies from the first time sample are shown; however, the system records the entire transient decay, and this will enable development of more advanced processing schemes. We anticipate that improved data processing methods will increase the resolving capabilities of the system and any future variants. In terms of the potential for UXO discrimination, we are encouraged by experimental and theoretical results from ground-based systems. Barrow and Nelson (2003) show that in many cases it is possible to distinguish exploded fragments from unexploded shells using frequency-domain EM measurements. Algorithms developed for ground-based time-domain data by Pasion and Oldenburg (2001) may prove useful for helicopter transient EM data as well. Although we did not specifically address the discrimination capabilities of the ORAGS-TEM system based on its transient decay properties, this is currently an active area of research for our group, and we plan to report results in the near future. There are clear and systematic differences visible in the profile data over different types of ordnance. In previous shakedown flights, we have noted different decay rates over a variety of test objects (Beard et al., 2002). We therefore anticipate that ORAGS-TEM data can be successfully used for ordnance discrimination. Preliminary results indicate that the 90-Hz base frequency will be more effective than the 270-Hz base for such discrimination. The longer cycle time provides an increased time to fully energize the target, and the longer off time allows more complete signal decay.

CONCLUSIONS

The ORAGS-TEM system that can not only detect bombs and large caliber ordnance, as did a prototype system based on the EM-61 (Doll et al., 2004), but can detect smaller caliber items as well (e.g., 81-mm mortar rounds, 60-mm illumination rounds) at survey heights of 1–2 m. The ability to detect these smaller types of ordnance is greatly dependent on survey height. EM fields decay sharply with increasing target-receiver separation such that at survey heights of 3–4 m, only large caliber rounds and bombs can be reliably detected. Using simple differencing of small receiver coil outputs, the vertical-gradient receiver configuration did not significantly improve signal-to-noise at low survey heights. Where it did improve SNR, the advantage was small, and disappeared at greater survey heights.

The present system is capable of detecting and mapping buried non-UXO metallic objects such as pipes and other infrastructure. With appropriate calibration and base frequency selection, we anticipate that the system should also be effective in other non-UXO applications as a tool for mapping ground conductivity.

ACKNOWLEDGMENTS

This work was funded by the Environmental Security Technology Certification Program under the direction of Jeffrey Marqusee and Anne Andrews, and supported by Scott Millhouse at the U.S. Army Corps of Engineers Mandatory Center of Excellence for Ordnance and Explosives, Huntsville, Alabama. Oak Ridge National Laboratory is managed by UT-Battelle, LLC for the U.S. Department of Energy under contract DE-AC05-00OR22725. A contractor of the U.S. Government has authored the submitted manuscript. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes. The composite fiber frame for the ORAGS-TEM system was designed by James Mewett of Airtech Canada. National Helicopters Inc. of Bolton, Ontario flew, Canada, the BBR survey. Chris Kellar was the pilot, Marcus Watson the field operator, and Dan Henderson the field engineer. We thank the Oglala Sioux Nation for allowing access to the Pine Ridge Reservation where the test site is located. Suggestions from anonymous reviewers and from the assistant editor improved the clarity of this work.

REFERENCES

Barrow, B., and Nelson H. H., 2003, Comparison of EMI measurements on large projectiles and on exploded projectile fragments: Proceedings of 2003 SAGEEP Symposium, Expanded Abstracts, 1399–1405, on CD.

Beard, L. P., Doll, W. E., Gamey, T. J., Holladay, J. S., and Lee, J., 2003, Aspects of system design for airborne electromagnetic detection of unexploded ordnance: Proceedings of 2003 SAGEEP Symposium, Expanded Abstracts, 1445–1454.

Beard, L. P., Doll, W. E., Gamey, T. J., Holladay, J. S., Lee, J., and Bell, D. T., 2002, A helicopter electromagnetic system for UXO mapping: Proceedings of 2002 UXO/Countermine Forum, Expanded Abstracts.

Bowers, R. J., and Bidwell, B. A., 1999, Geophysics and UXO detection: The Leading Edge, **18**, 1389–1391.

Doll, W. E., Gamey, T. J., Beard, L. P., Bell, D. T., and Holladay, J. S., 2003, Recent advances in airborne survey technology yield performance approaching ground-based surveys: The Leading Edge, **22**, 420–425.

Doll, W. E., Gamey, T. J., and Holladay, J. S., 2001, Current research into airborne UXO detection: Proceedings of 2001 SAGEEP Symposium, Expanded Abstracts, UX2-3.

Doll, W. E., Gamey, T. J., Holladay, J. S., and Lee, J. L. C., 2004, Viability of an airborne electromagnetic system for mapping of shallow buried metal, *in* D. W. Butler, ed., Near surface geophysics: volume 2, Applications and case histories: SEG, in press.

Doll, W. E., Nyquist, J. E., Beard, L. P., and Gamey, T. J., 2000, Airborne geophysical surveying for hazardous waste site characterization on the Oak Ridge Reservation, Tennessee: Geophysics, **65**, 1372–1387.

Ferraccioli, F., Bozzo, E., and Armadillo, E., 2002, A high-resolution aeromagnetic field test in Friuli: Towards developing remote location of buried ferro-magnetic objects: Annals of Geophysics, **45**, 219–232.

Gamey, T. J., Doll, W. E., Beard, L. P., and Bell, D. T., 2003, Analysis of noise coherence in airborne vertical magnetic gradients for UXO detection: Proceedings of 2003 SAGEEP Symposium, Expanded Abstract, 1387–1398.

Gamey, T. J., and Mahler, R., 1999, A comparison of towed and mounted helicopter magnetometer systems for UXO detection: Proceedings of 1999 SAGEEP Symposium, Expanded Abstracts, 783–792.

Nabighian, M. N., and Macnae, J. C., 1991, Time domain electromagnetic prospecting methods, *in* M. E. Nabighian, ed., Electromagnetic methods in applied geophysics, **2**: SEG, 427–520.

Pasion, L. R., and Oldenburg, D. W., 2001, A discrimination algorithm for UXO using time-domain electromagnetics: Journal of Environmental and Engineering Geophysics, **6**, 91–102.