DEVELOPMENT AND EVALUATION OF A SECOND-GENERATION AIRBORNE ELECTROMAGNETIC SYSTEM FOR DETECTION OF UNEXPLODED ORDNANCE

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Abstract

On the basis of a successful prototype test, we have begun development of a new airborne electromagnetic system for detection of unexploded ordnance. The design is based on an investigation of design parameters and a series of noise measurements. The noise tests were designed to determine optimal locations for transmitters and receivers and to characterize the relative noise contributions of the helicopter with and without its engine running, as well as to distinguish between noise that is helicopter-generated and that which is induced in the helicopter by the electromagnetic transmitter. Data were acquired with the second-generation prototype in December 2001, and completion of a production system is anticipated approximately one year later.

Introduction

In recent years, an Oak Ridge National Laboratory led team has committed significant effort toward development of airborne geophysical systems for the detection and mapping of unexploded ordnance. Until recently, most of our effort was devoted to testing and refinement of total field magnetometer systems for this application (Doll et al, 1999, Gamey et al., 2000; Doll et al., 2001). These systems have now passed through four generations of enhancement and have been successfully deployed at several sites. As the total field systems have matured, we have directed our efforts to other system designs, such as measured vertical gradient systems (Gamey et al., this volume), designed to provide greater sensitivity, and electromagnetic inductive (EMI) systems. The EMI systems are desirable for at least three situations: 1) where geologic effects cause detrimental noise in magnetic data, 2) where some or all of the UXO in an area of concern is composed of non-ferrous metals that cannot be detected with magnetic systems, or 3) where probability of detection can be enhanced through use of multiple sensor types.

In August and September 2000, we fielded a first-generation airborne EMI prototype for detection and mapping of unexploded ordnance. This system was based on a modified Geonics EM61 and integrated with the Oak Ridge Airborne Geophysical System (ORAGS) positioning and data recording system. Results from this first prototype test were presented at SAGEEP 2001 (Doll et al., 2001). The success of the first generation prototype provided motivation for focused development of an airborne electromagnetic UXO detection system by evaluation of the full range of design options through field measurements and reconsideration of theoretical constraints. In this paper, we report on the first year of a two-year development project. This includes design considerations, noise measurement results, and initial field tests.

Design considerations

The design of an airborne system for detection of UXO must begin with consideration of the differences between an airborne UXO detecting system and conventional airborne EM systems which are designed to detect geologic features, not man-made metallic objects. The requirements for a UXO system can be summarized as follows:

1. Target resistivity and size, depth, and other attributes have response characteristics that differ significantly from geologic targets. System design considerations must address these differences.
2. The system needs to be responsive to a wide range of UXO.
3. At this early stage of development, detection takes priority over discrimination. It is probably not necessary to design a calibrated system that very accurately characterizes the electrical properties of the ordnance.

Several summaries have been published to describe the development of airborne EMI systems, most recently Fountain (1998). Considerable effort has been devoted to enhancement of ground-based EMI systems for UXO and to the development of techniques to process the resultant data, but to our knowledge, airborne EMI systems for UXO detection have not been reported, other than the prototype test that we reported in Doll et al., 2001.

Frequency Domain vs. Time Domain

Both frequency domain and time domain EMI systems have been successful in ground-based detection of UXO, and both designs have been used in airborne EMI systems for mining applications. An often-quoted advantage of time domain systems is that they have a greater depth of detection than frequency domain systems based in large part on Australian exploration experiences. However, it may simply be that deep sensing time domain systems have used larger magnetic moments than frequency domain systems. One hindrance to deep detection in frequency domain systems comes from having to measure at low frequencies a very weak secondary field in the presence of a primary field that may be hundreds of times stronger and in the presence of ambient (and for airborne systems, microphonic) noise that increases rapidly at progressively lower frequencies. In addition, the weak secondary response of near surface materials (even in a relatively resistive environment) to frequency domain primary fields is always present, superposed on the potentially weak response of the deeper target. In a time domain system, the response of surficial materials has typically decayed before the prime EM response delay time window, and so may not contribute to the observed anomaly of the target. With regard to the presence of the primary field at the time of secondary field measurement in frequency domain measurements, coil alignment and separation then becomes especially critical. In most time domain systems, the transmitter is switched off during the principal EM measurement portion of the system waveform, and so the received signal is purely secondary.

Turn off times in time domain EM systems have proven problematic for the interpretation of near-surface layered structures in engineering and environmental applications (e.g. Pellerin and Alumbaugh, 1997). In the time taken for the transmitter current to shut off, the maximum of the induced current loop in the ground has already passed several meters (even 10s of meters) into the earth. This is demonstrable from the equation for diffusion depth $z = \sqrt{2t/\sigma\mu}$ (Nabighian and Macnae, 1991). For example, if the first time gate is located at 1 ms after transmitter turnoff, then over a non-magnetic 100 ohm-m (σ = 0.01 S/m) earth the induced current loop will have already penetrated over 12 m into the earth. For UXO applications this is less a problem because ordnance detectable from an airborne platform usually exhibits relatively long decay times, so current will persist in large pieces of conductive ordnance for easily measurable times. In fact, it has been demonstrated that even relatively small pieces of compact ordnance display time constants of 1 ms or longer; their relatively weak EM responses stem from their small physical dimensions.

Frequency domain adherents emphasize the capability of frequency domain systems to reject 60 Hz power line noise, thus making these systems more useful in urbanized areas. The relatively low frequency-domain transmitter moments achievable in handheld or airborne multi-frequency systems, coupled with a limited or poor choice of frequencies, could limit the proportion of UXO detected. On the other hand, a tunable multi-frequency system could allow the system operator to choose the most responsive set of frequencies for the suspected UXO.

An objective comparison of existing commercial time domain and frequency domain EM systems used as generalized survey tools would on balance show no clear universal advantages of one over the other. On one hand, if one factors in practical instrumentation considerations, time domain measurements may continue to be the method of choice for discrimination of conductive targets having relatively long time constants from poorly-conducting geological features displaying shorter time constants, such as UXO. We have chosen to develop a system that is primarily a time-domain system as a result of this analysis.

Ground or Airborne Transmitter

All of our noise measurements were made with instruments in which the transmitter and receiver are mounted on the same frame. This geometry is appropriate for evaluating systems that are mounted on booms that attach directly to the helicopter. An advantage of this arrangement is that anomalies become more predictable if the transmitter illuminates the target from overhead. Another advantage is logistical—the entire system is in one package. A disadvantage is that the source must be small enough to be carried by a helicopter. If instead of being carried by the aircraft the transmitter is placed on the ground, the size of the transmitting loop (or linear, grounded wire source) can be made much larger. The transmitter moment could energize a large area while an aircraft on which the receiver is mounted flies over the survey area. Elliot (1998) describes such an arrangement as applied to sulfide exploration in Australia. The primary advantage of the FLAIRTEM system, as it is called, is that it is more sensitive to conductive bodies at depths greater than 100 m, and so can detect mineral deposits through thick overburden. In UXO surveying the targets are within a few meters of the surface, negating the advantage of greater detection depth. A FLAIRTEM type system would no doubt energize near surface conductors as well as deeper ones and so could in principle be used for UXO surveys. However, the cost and logistical disadvantage of laying out, picking up and maintaining/ guarding large transmitter loops (which are easily damaged by animals, vehicles, or vandals, and carry hazardous levels of high voltage), particularly in rugged terrain, would seem to outweigh any advantage incurred by increased transmitter power, especially since on-board transmitters appear to suffice for energizing highly conductive UXO buried at shallow depths.

The strongest argument in favor of using airborne EM transmitters as compared to large, high-powered surface-based transmitters for UXO detection is based on the fact that the AEM response of a UXO target is directly proportional to the strength of the transmitted field illuminating the target. While the transmitted magnetic moment (a commonly used measure of the efficacy of EM systems) of a large loop is directly proportional to the loop area, the transmitted magnetic field over the majority of the loop area *decreases* as the loop area *increases*, for a given transmitter current. This yields the intuitively unexpected result that it is possible in practical terms to generate a far larger transmitted field at the location of the target from an airborne transmitter than can be achieved through the use of a much higher-power large surface-based transmitter loop, despite the fact that the large loop might generate a much larger moment.

Noise measurements

The noise of the platform (helicopter) as well as the theoretical response in the absence of noise, described earlier, must be considered in the design of an optimal airborne EMI system for UXO. The optimal approach would be to measure the passive and active noise over a grid of points while the helicopter is in flight. With limited resources, we were able to conduct noise tests around a Bell 206L helicopter with an EM63 and the EM61AB prototype coils. The active EM63 data were acquired at a test site in Arkansas in three conditions (Figure 1): a) before placing the helicopter on the survey grid, b) with the helicopter at the center of the survey grid and turned off, and c) with the helicopter on the ground at the center of the grid and operating at throttle approximating that used while in flight. The data were measured with the EM63 over an area that extends approximately 6m to the front and sides of the helicopter, where previous experience indicates that we could install the EM coils. Data were recorded at 20 time gates, positioned between 0.2 and 7.1ms. Sample rate was approximately 4 Hz. Figure 1 shows the RMS noise for the three conditions described above for EM63 channel 5 (0.290 ms). The three plots are at different scales, as shown by the color bars. The background noise of the site is as large as 6.1mV in parts of the survey grid. When the helicopter is present at the site, the RMS noise extends beyond 100mV in some places, and when the engine is running it extend beyond 200mV in places. Whether the helicopter is on or off, the majority of the induced noise occurs within about 3.0-3.5m

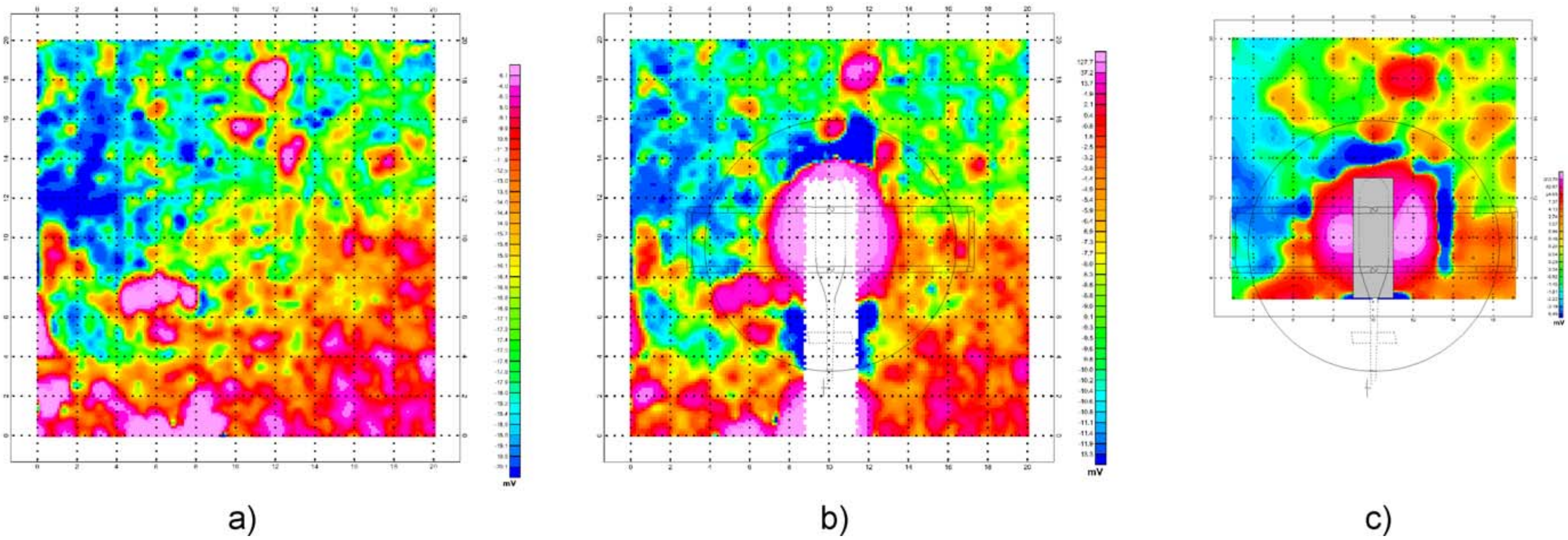

Figure 1. Noise measurements acquired at a test site in Arkansas with an EM63 for channel 5 (0.290ms). a) data acquired over a 2m grid without the helicopter present, showing the background noise at the site (scale maximum is 6.1 mV); b) noise measurements acquired in survey mode with the helicopter present at the site, but with its engine off (scale maximum is 127.7 mV); c) RMS noise measurements acquired over a 1m grid with the helicopter present with its engine running (scale maximum is 203.7 mV).

of the tow hook at x=10, y=10 on all images. Similar plots have been prepared for other channels and show similar results. It is interesting to note that the EM61AB prototype measurements were made with the 1.5 X 2m transmitter coil centered at about 2.5m from the center of the helicopter, and 0.5 X 1.0m receiving coils centered at 2.0 and 3.0m from the helicopter. The Arkansas noise data suggests significant advantages to placing the coils further from the aircraft.

Passive data were acquired similarly in Tennessee using 1) an EM63 with transmitter off and 2) the EM61AB with transmitter off. The purpose was to discriminate between EM63-induced noise and noise that originates in the helicopter. Figure 2 shows an example of the results from these tests. As before, the results are for channel 5 of the EM63. Figure 2 shows data acquired with the transmitter off, which compares with Figure 1c, acquired at a different site (Arkansas) with the transmitter on. This indicates that with the helicopter on but the EM transmitter turned off, noise reaches amplitudes of about 25 mV. Similarly, with the helicopter off and transmitter off, a noise level of about 2 mV was measured.

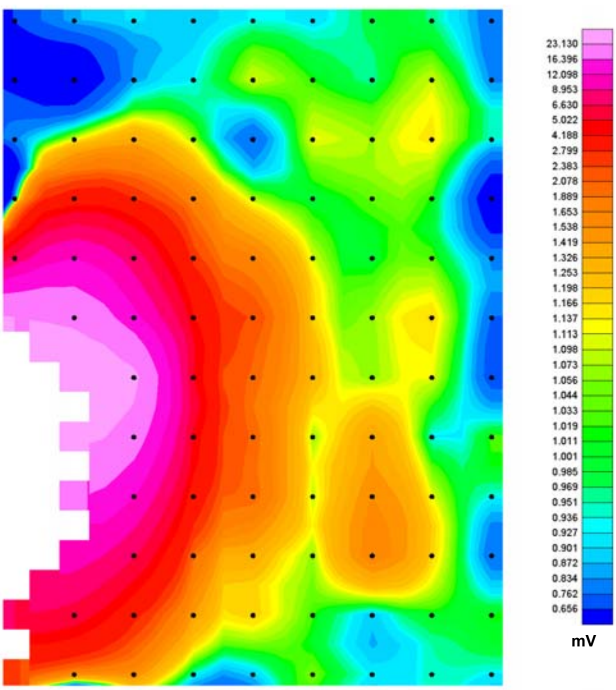

Figure 2. Noise data acquired over a 2m grid at a Tennessee test site with helicopter engine running and EM63 transmitter off.

In addition to the spatial behavior of EM noise, the influence of the helicopter engine and EM transmitter induced response, it is also important to know the character of noise as a function of time. Figure 3 shows the decay for a series of transmissions while the EM63 was stationary at position x=12, y=11 (see Fig 1.), 2m from the centerline of the helicopter while it is running. Beyond 8-10ms, the amplitude of the signal is several orders of magnitude smaller than in the first few ms, and for this location, noise becomes dominant at that time range. Further from the helicopter, the noise is reduce substantially on all time gates, as represented by channel 5 in Figure 1.

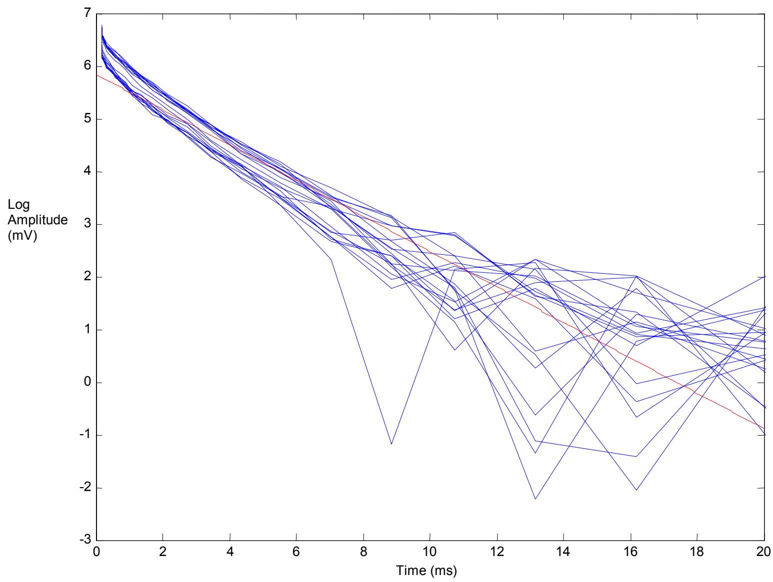

Figure 3. Noise test data acquired with an EM63, consisting of repeated transmissions while the EM63 is stationary at a position 2m from the centerline of the helicopter.

Prototype System Design

As a result of our analysis and noise testing, we have designed a second-generation prototype that will be used to test selected attributes for a final system. The prototype was tested for the first time in December 2001. Figure 4 is a photograph showing the system in flight. The transmitter loop is attached to a pair of booms with a total length of 12m and separation of 3m. Initial tests with this system included an evaluation of selected base frequencies, configuration tests, altitude tests, and noise tests.

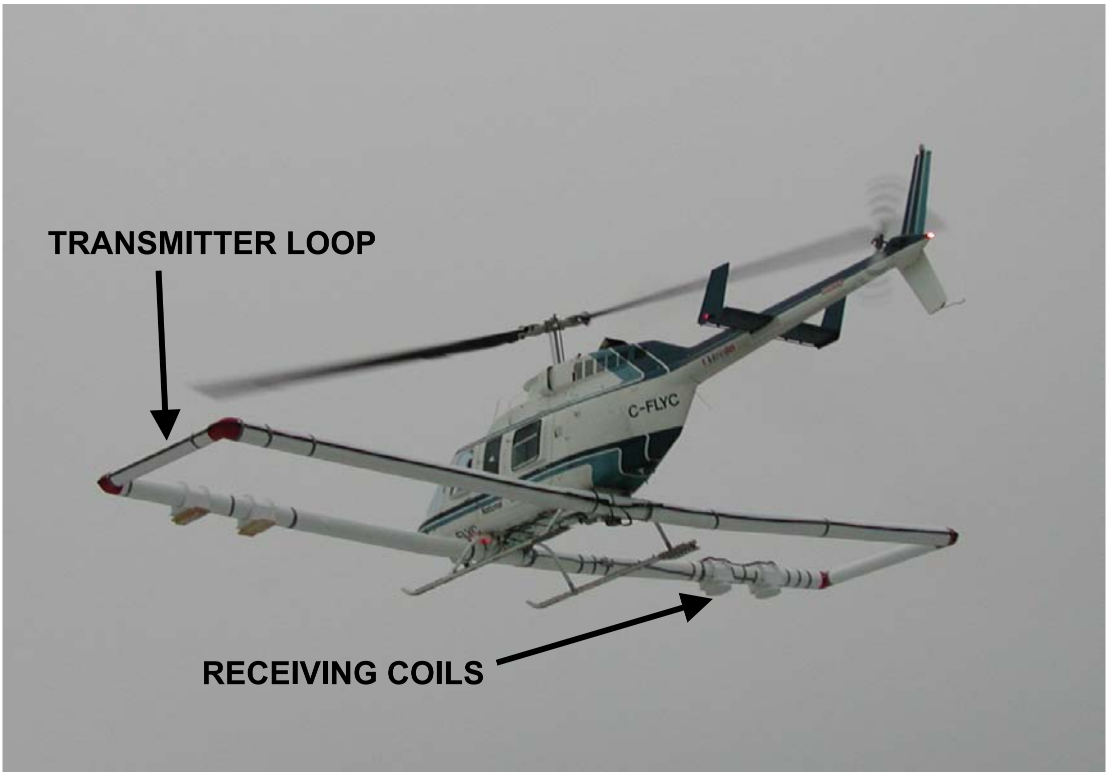

Figure 4. Photograph of the second-generation EM prototype system.

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