Recent advances in airborne survey technology yield performance approaching ground-based surveys

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Airborne magnetic and electromagnetic systems have been very effective over the years for mineral prospecting and in support of petroleum exploration. More recently, these towed-bird systems, operating at sensor altitudes of 30-50 m, have supported environmental investigations. The towed-bird systems can provide regional data for site investigations, such as locating or delimiting the boundaries of waste areas, identifying geologic contacts that influence environmental issues, or mapping saline intrusion. However, these conventional systems cannot provide the resolution required in many environmental and engineering problems because the distance between sensors and target objects is too great. Ground-based surveys are often suitable for addressing these problems but, for many sites, the area can be too large to be expediently addressed with surface geophysics. Contamination of government land with unexploded ordnance (UXO) is one such large-scale problem.

As military bases are being closed and returned to civilian use, the removal of UXO has become a critical problem. By one estimate, about 11 million acres within the United States, roughly the sum of the areas of the states of New Hampshire and Vermont, is contaminated with UXO. This includes Department of Defense (DoD) sites, Department of Energy (DOE) sites, Native American sites, and National Park lands. At some DoD sites, large areas are currently off limits for training pending removal of UXO. In other parts of the world, UXO threatens people's lives every day.

In the 1990s, two coauthors of this article, Holladay and Gamey, began to address the UXO problem while working at Aerodat in Toronto. They devised a three-magnetometer system, the HM-3, in which the sensors were mounted in booms attached directly to the helicopter. This architecture provided an opportunity for the pilot to safely fly much closer to the surface. During subsequent joint projects with Oak Ridge National Laboratory (ORNL) researchers, both system and operational parameters were adjusted, and a successful demonstration of the HM-3 system for UXO as small as 4 kg was completed in September 1999. Since that time, the authors have developed improved magnetic systems and time-domain electromagnetic systems for detection and mapping of UXO and other metallic objects of similar size. These are collectively referred to as the Oak Ridge Airborne Geophysical System (ORAGS).

The most recent of the total field magnetometer systems is the ORAGS-Arrowhead system (Figure 1). The sidebooms and foreboom house eight cesium vapor magnetometers at a nominal spacing of 1.7 m, with two magnetometers at the ends of the sidebooms and four spaced evenly across the v-shaped foreboom. Boom-mounting allows operation at altitudes as low as 1-2 m above ground level (AGL), much lower than possible with conventional towed bird systems. This provides resolution that approaches that of ground-based systems.

The sensor positioning is designed to minimize noise from the helicopter rotor and other sources while maintaining a

Figure 1. *The ORAGS-Arrowhead total field magnetometer in operation.*

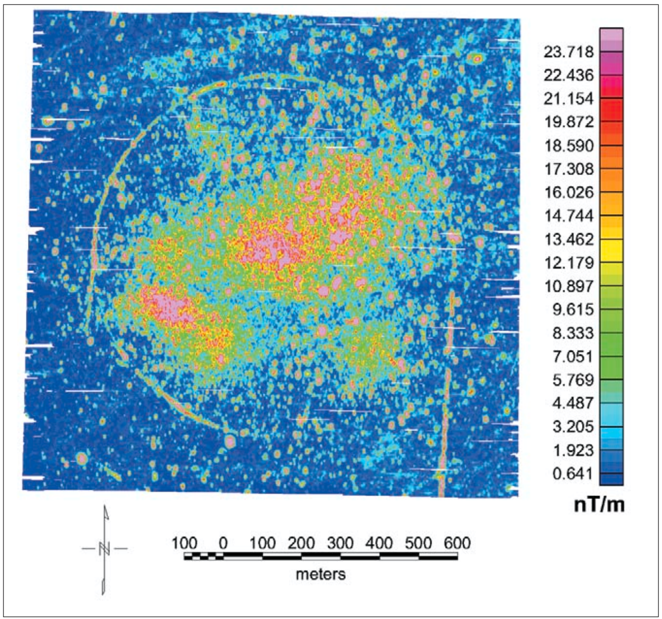

Figure 2. *Analytic signal map of a bombing target in New Mexico, derived from airborne magnetic data.*

Figure 3. *Photographs of the M-38 practice bombs at Pueblo.*

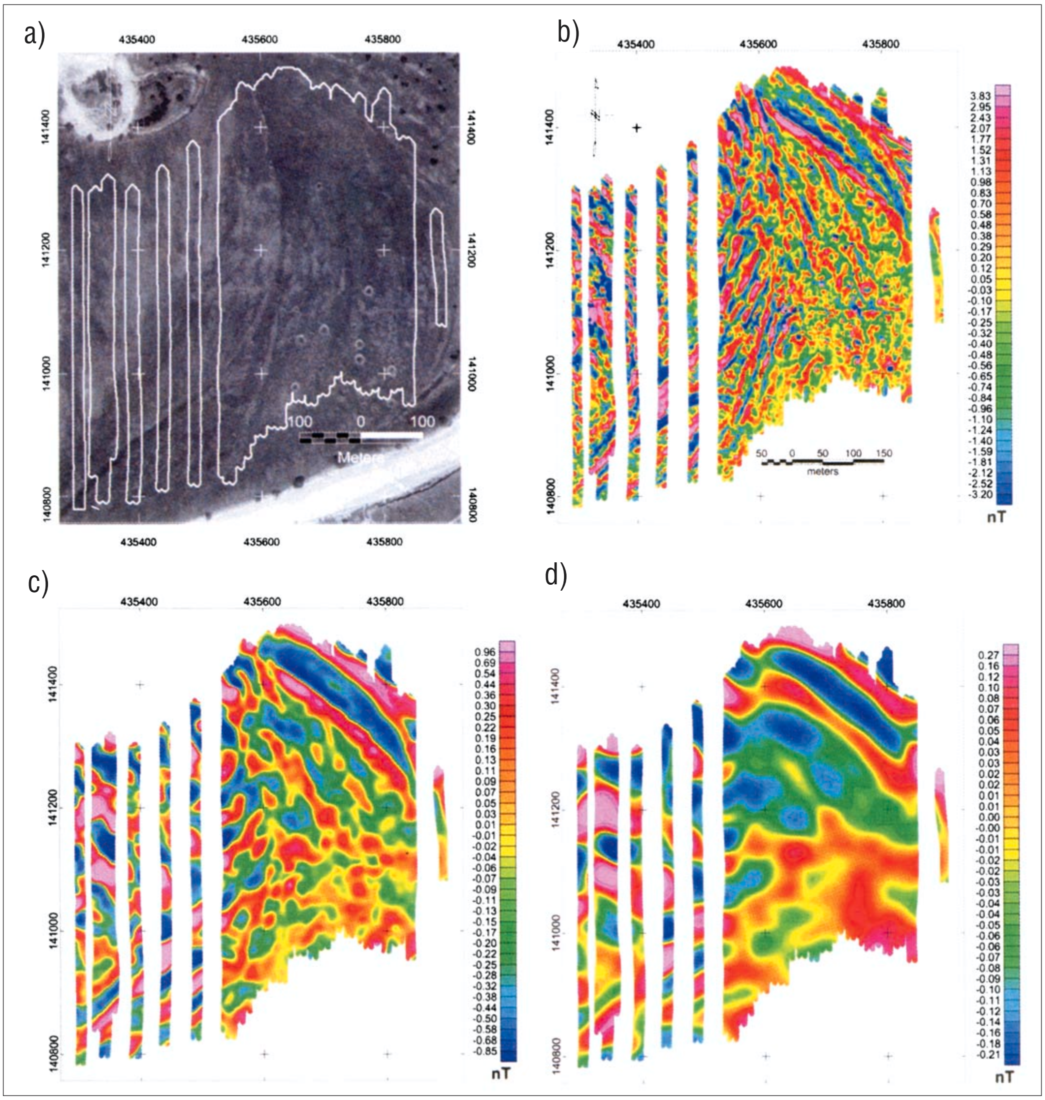

Figure 4. Comparison of airborne magnetic map with orthophoto segment and upward continued maps for a meander of the White River, in the South Dakota Badlands: (a) orthophoto map of the site; (b) residual magnetic anomaly map acquired at 2 m altitude; (c) data from 2 m upward-continued to 12 m; and (d) data from 2 m upward continued to 32 m altitude.

weight distribution that optimizes flight performance and, above all, safety. All data are recorded on a PC-based console that samples the magnetometers and key analog inputs (such as a fluxgate magnetometer) at 1.2 kHz and records laser-derived altitude and GPS position at the full output rates of those devices. The magnetometer data are downsampled, typically to 120 Hz, and the other data are interpolated to the same sample frequency as the downsampled magnetometer data. Navigation is directed by an Agnav RT-DGPS system with Racal satellite real-time correction. Aircraft position is recorded on the system console and updated by postprocessing with a DGPS base station to provide accuracy of 0.2 m or better. Under optimal flight conditions, the system acquires data over a 12-m swath at 1.7-m sensor spacing at a flight height of 1.5-m AGL. An Ashtech ADU-2 GPS-based system monitors the attitude of the system to provide accurate positioning for each sensor. ORAGS systems are typically operated at an air speed of 50 knots. This allows full coverage acquisition of a rate of about 50-70 acres per hour under favorable conditions.

Figure 2 is an analytic signal map of a bombing target in New Mexico, derived from ORAGS-Arrowhead data. Most anomalies in this map are associated with M-38 sand- and concrete-filled practice bombs with spotting charges. These are sheet metal bombs, about 0.8 m long with a ferrous steel content of about 10 kg. Anomaly picks for this target were selected with a threshold of about 1.5 nT/m, corresponding to a few kg of ferrous metal. Many bombs and fragments are at or near the surface (Figure 3), but some are buried at depths that usually don't exceed 1 m. The 900-m diameter ring about the center of the target is associated with a berm of soil that was plowed so that the target could be seen from the air. This is a standard feature at many bombing targets.

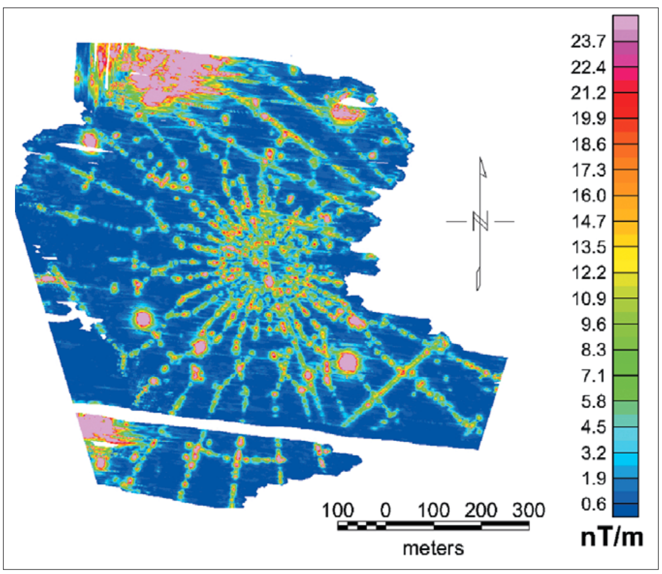

Figure 5. Analytic signal map for a site in Maryland showing anomalies associated with a network of piping that had been overlooked in more localized ground-based surveys.

Non-UXO applications for this technology. In the course of acquiring data at UXO sites throughout the United States, we have observed that the ORAGS boom-mounted magnetometer system is also suitable for high-resolution mapping of geologic features. Data from a meander in the White River on the Badlands Bombing Range in southwestern South Dakota demonstrate the sensitivity of the system and advantages over

Figure 6. ORAGS-VG vertical magnetic gradient system.

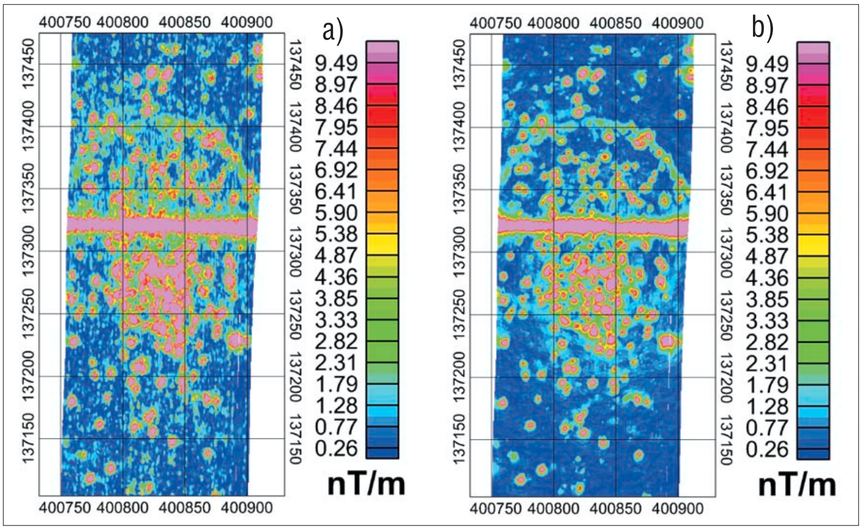

Figure 7. Analytic signal maps for a bombing target in South Dakota: (a) analytic signal derived from total field measurements with the ORAGS-Arrowhead system; (b) analytic signal derived from measured vertical gradient with the ORAGS-VG system. Horizontal scale is in meters.

systems that operate at higher altitudes.

Figure 4 shows the relationship between the geophysical survey area and site geomorphology for a data set acquired to map UXO within a meander of the White River. The orthophoto image from the site (Figure 4a) shows several impact craters associated with ordnance. The ORAGS residual magnetic anomaly map for 2-m sensor altitude shows magnetic anomalies that are collocated with these craters, indicating that ordnance or ordnance debris is still present in or beneath the craters (Figure 4b). The magnetic data were acquired at full coverage over the portion of the site where the craters had been observed and additional swaths were acquired at greater line separation around the primary target. Each swath consists of eight profile lines. The dominant features on the magnetic anomaly map are not the ordnance anomalies, but a series of crosscutting anomalies that are presumably associated with deposition of iron-bearing minerals along the streambed. We believe that this may reflect differential deposition of denser (iron-bearing) minerals along the high-energy outer banks of the river meanders.

Figures 4c and 4d show the upward continuation of the data from Figure 4b to altitudes of 12 m and 32 m. The purpose is to demonstrate in a simplistic manner the difference between data collected with the ORAGS system and data that could be acquired with conventional airborne surveys. These indicate that the resolution of a conventional survey would be too low to detect the important magnetic anomalies. In fact, towed-bird surveys would have even poorer resolution than shown in Figure 4d because line spacing is considerably larger in standard surveys.

Figure 5 shows an analytic signal map for a site in Maryland where many previous ground-based geophysical surveys had been conducted. The airborne data set delineated a spider web of underground pipes that had been overlooked in the preparation and interpretation of ground-based surveys. Such a network of conductors has almost certainly had a negative impact on the processing and interpretation of the ground surveys. The network would not have been detected with a conventional airborne survey at conventional altitudes, as demonstrated by the data in Figure 4. This demonstrates the value of using a boom-mounted airborne survey in the early stages of a site investigation to provide a backdrop for subsequent ground-based surveys. Infrastructure mapping is an appropriate task for these airborne systems at many large government and industrial sites.

For mineral investigations, the data from the system might be used in two different ways. Where data can be acquired at low altitudes (<5 m AGL), the ORAGS system can be used for high-resolution mapping, as with environmental surveys. At higher altitudes, the dense magnetometer configuration could be used to acquire various types of horizontal gradient data (e.g. measured first order, second order, etc.). Similarly, the ORAGS system could be used to support petroleum surveys, as a reconnaissance tool for mapping weak magnetic anomalies that might be petroleum indicators (e.g. Henderson et al., 1984) or could otherwise influence selection of seismic survey sites. Elsewhere in the Badlands, we have observed linear magnetic anomalies in flat-lying sediments that may be associated with chemical alteration or deposition of magnetic minerals along faults or fracture zones. Previous research (e.g. Burazer et al., 2001) has focused on developing processing methods to extract weak anomalies from data acquired at higher altitudes, whereas the ORAGS system has the sensitivity to detect these anomalies without advanced processing. The system might also be used as a tool for identifying infrastructure or cultural interference sources and geologic features within an area that has already been selected for a seismic survey.

Vertical magnetic gradient system. For conventional airborne systems, there is an ongoing debate regarding the benefits of measured vertical magnetic gradient versus calculated vertical magnetic gradient. The latter is derived from gridded total field maps using Fourier analysis or other methods. In previous work (e.g. Doll et al., 2000), we found the calculated gradient to be unsatisfactory for low-altitude measurements. To further investigate this issue, we developed a vertical gradient system, using gradiometer pods and referred to as the ORAGS-VG system (Figure 6). Various configurations were tested in addition to the 1 m vertical/1 m horizontal magnetometer separations shown in Figure 6. In Figure 7, we show analytic signal maps derived from (a) total magnetic field data (calculated vertical gradient) and (b) measured vertical gradient, using the 1 × 1 m separations in Figure 6. An east-trending barbed-wire fence crosses the center of the target.

We note that most of the anomalies are better isolated, flight line noise is reduced, and the overall character of the map is significantly quieter on the measured gradient analytic signal map.

Figure 8. ORAGS-TEM system in transit near the Black Hills, South Dakota.

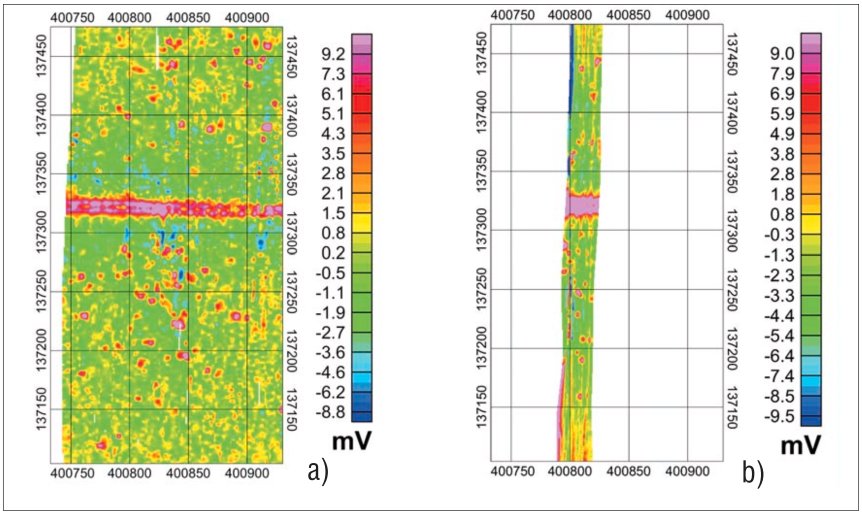

***Figure 9.** ORAGS-TEM measurements with (a) large loop receiver and (b) small loop receiver at a bombing target in South Dakota, corresponding to the magnetic data shown in Figure 6. Data were acquired at 1-m nominal flight line spacing with the small loop receiver, as compared to 3-m flight line spacing with the large loop receiver. As a result, a smaller area was surveyed with the small loop receiver. Horizontal scale is in meters.*

Electromagnetic system for UXO mapping. We have also developed a boom-mounted airborne time-domain electromagnetic (EM) system, principally for UXO mapping and detection. There are four primary reasons for this research and development initiative. First, not all UXO is ferrous. An EM system is capable of detecting aluminum, brass, or stainless steel objects where the magnetic system will not. Second, EM systems can perform better than magnetometer systems where geologic interference from basalts or other mafic lithologies is problematic. This has been a factor in sensor selection for ground-based surveys in Hawaii and the southwestern United States. Third, EM systems provide more opportunities for analyses that aim to distinguish between different types of UXO or between UXO and non-UXO, because they allow more parameters to be measured (e.g. multiple time gates in a time-domain system or multiple frequencies in a frequency-domain system) and subsequently inverted. Finally, the potential for coacquisition of electromagnetic and magnetic data provides enhanced opportunities for discrimination and ultimately a reduction in the number of anomalies that must be excavated.

Our current EM system consists of a large 3 × 12 m transmitter loop with two options for receiving coils (Figure 8). Large loop receivers consist of a single turn on the outermost 2.7 × 2.7 m portion of the boom. The small diameter multiturn receiving coils measured 23 × 60 cm, and are positioned midway between the leading and trailing booms. Because the current system is an experimental prototype, it is only a two-channel system. Footprints for the small and large coils are about 1 m and 3 m respectively when flying at a minimum survey altitude of about 1.0-1.5m. Construction of the “production” six-channel EM system should be completed by the third quarter of 2003.

Electromagnetic data were acquired with the ORAGS-TEM system for the same target in South Dakota as in Figure 7. These results are shown in Figure 9. The small loop receiver has better resolution than the large loop receiver, but in its current configuration requires more flight passes due to smaller footprint. The 150-m diameter target berm is not seen on the EM map, though it is obvious on the magnetic map. Anomalies in a 15-20 m zone straddling the east-trending fence at the center of the target are undetected, due to the increased flight height required to pass over the fence.

Summary. Three new systems demonstrate that airborne geophysical systems are increasingly effective for UXO detection and other environmental and engineering applications. The ORAGS-Arrowhead system represents a mature stage of development, resulting from 15 “production” surveys throughout the United States. The ORAGS-VG and ORAGS-TEM systems have been thoroughly field-tested and are ready to be transitioned into production systems. We anticipate that the use of these systems will be extended beyond UXO surveys to mapping of infrastructure in brownfields, or other environmental applications, and believe that it can also be extended to a broad range of resource exploration applications where high resolution is desired but unattainable with conventional airborne systems.

Suggested reading. “Aspects of system design for airborne electromagnetic detection of unexploded ordnance” by Beard et al. (Extended abstract to be presented at SAGEEP, 2003). “Magnetic data processing for hydrocarbon exploration in the Pannonian Basin, Yugoslavia” by Burazer et al. (GEOPHYSICS, 2001). “Current research into airborne UXO detection” by Doll et al. (*SAGEEP Proceedings*, 2001). “Analysis of Noise Coherence in Airborne Magnetic Gradients for UXO Detection” by Gamey et al. (Extended abstract, to be presented at SAGEEP, 2003). “Comparison of Towed and Mounted Helicopter Magnetometer Systems for UXO Detection” by Gamey and Mahler (*SAGEEP Proceedings*, 1999). “Airborne EM and magnetic surveys find fault(s) with Sulphur Bank Mercury Fund Superfund site” by Hammack and Mabie (*TLE*, 2002). “Direct indication of hydrocarbons from airborne magnetics” by Henderson et al. (*Exploration Geophysics*, 1984). TLE

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