Development of Airborne Magnetic and Electromagnetic Systems for Mapping and Detection of UXO and Other Shallow Metallic Objects

W. E. Doll, L. P. Beard, T. J. Gamey, and D. T. Bell, Oak Ridge National Laboratory, Oak Ridge, TN USA, 37830
J. S. Holladay, Geosensors Inc., Toronto, Ontario, Canada

Summary

Boom-mounted airborne magnetic and electromagnetic systems represent a significant advance in airborne technology for engineering and environmental applications. Although most surveys to date have been directed toward unexploded ordnance (UXO), the systems are appropriate for efficiently addressing a wide number of problems that are important to near-surface geophysicists.

Introduction

Airborne geophysical systems have been in use since 1943 (Hildenbrand et al., 1990). These systems used airborne magnetometers for submarine detection and geophysical mapping. Airborne electromagnetic systems were introduced in the 1950s (Barringer et al., 1990) for mineral exploration. These early magnetic and electromagnetic systems were mounted on fixed wing aircraft. In the 1960s helicopter systems were introduced in which the electromagnetic components were mounted in towed birds, suspended from the helicopter on a cable, 30m or more in length.

For many years, environmental and engineering applications of airborne systems were limited to large scale problems (hundreds of m to km in dimension), such as saltwater intrusion, where the geophysical property of the target had sufficient contrast with background to be detectable at altitude. Airborne data were referenced where knowledge of regional features could help in understanding localized near-surface problems. However, airborne data were rarely acquired with the intent of addressing environmental or engineering problems.

In the 1990s, however, the use of helicopter systems for addressing near surface problems became more common. Pellerin and Labson (2003), have summarized a demonstration survey that was conducted by the U. S. Department of Energy at the Idaho National Environmental and Engineering Laboratory (INEEL). A 1993-1994 survey of the 143 km^2 Oak Ridge Reservation (Doll et al., 2000) is one of the earliest uses of airborne systems over a large site for addressing moderate-scale (about 10m or larger) environmental and engineering problems. This survey was conducted with an integrated magnetic, electromagnetic, and radiometric system at a large government site to identify unmapped waste areas and geologic features that might constrain transport of contaminants. The growing use of airborne systems for evaluating environmental and engineering problems can be represented by the number of papers presented at SAGEEP conferences between 1988 and 2004 (following Paine, 2003), as shown in Figure 1.

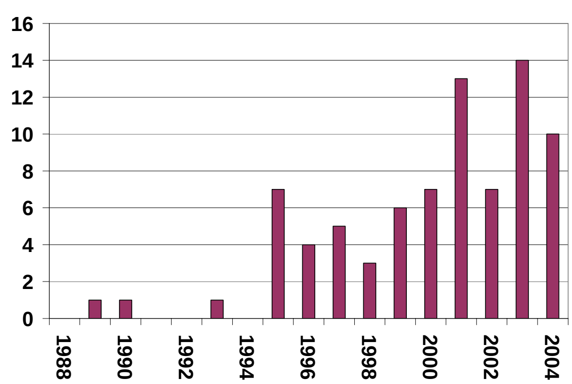

Figure 1. Number of SAGEEP papers related to airborne methods from 1988 to 2004 (after Paine, 2003).

In 1997, Aerodat Ltd. introduced the HM-3 boom-mounted magnetometer system, in which three cesium magnetometers were mounted at the tips of 6-m booms extending to the port, starboard, and front of a Bell 206 helicopter. By mounting the sensors in booms, it became possible to acquire data

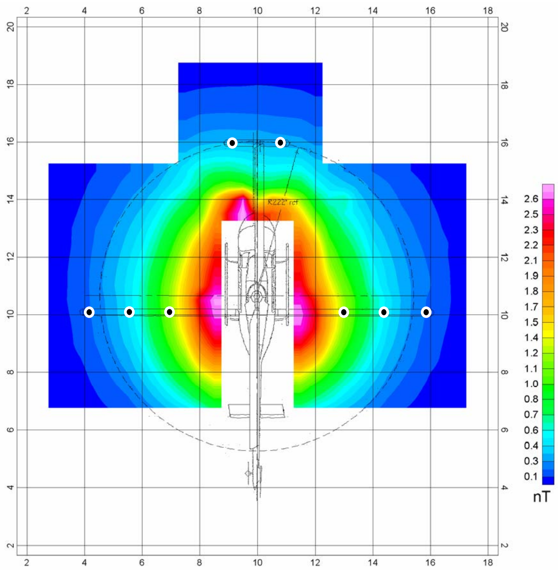

Figure 2. Geometry of the ORAGS-Hammerhead, an eight magnetometer airborne array. Magnetometer locations are shown as black dots. The background map shows the measured RMS noise, primarily 6.5 Hz rotor noise.

at much lower altitudes than with conventional towed bird systems. Large scale surveys for small targets (about 1m or smaller) became feasible. Initial field operations with the HM-3 had limited success, because data were acquired at an altitude (about 5m) that was too high and at a sample rate (20 Hz) that was too low (e.g. Doll et al., 1999). Data acquired at the Badlands Bombing Range (BBR) in South Dakota in 1999 were significantly improved and showed that airborne systems could detect metallic objects as small as a few kg (Gamey et al., 2000). This led to the development of more sensitive magnetometer systems and boom-mounted electromagnetic systems, described in this paper. The capability of acquiring data at altitudes of 1-3m above ground level (AGL) is the common thread that has made these systems successful.

Boom-mounted Magnetometer Systems

Five new systems have been developed by a research group led by Oak Ridge National Laboratory to improve upon the HM-3 system. These are collectively known as the Oak Ridge Airborne Geophysical Systems (ORAGS). The first of these is the ORAGS-Hammerhead system. This system has an array of eight cesium vapor magnetometers at 1.7m spacing. Two are located in a “T-bar” in front of the aircraft, and three are in each of the two side booms (Figure 2). The system console records at 1200 Hz, and we typically downsample the data to 60 Hz or 120 Hz before processing. Navigation is accomplished using a system that was designed for airborne agricultural spraying (“crop-dusting”). Altitude is monitored with a laser altimeter, and a post-processed, base station corrected global positioning system (GPS) provides location with an accuracy of a few tenths of a meter. This system has no attitude measurement system.

The ORAGS-Hammerhead has been replaced by a more advanced system, the ORAGS-Arrowhead system (Figure 3). This has the same number of magnetometers as the Hammerhead system, but they have been repositioned on a new boom structure, in order to reduce noise (Figure 3b). The altitude, navigation, and recording systems are the same as for the ORAGS-Hammerhead system. An improved positioning system and a GPS-based system for monitoring the pitch, roll, and yaw (attitude) of the helicopter were added to the Arrowhead system. This allows correction for locations of magnetometers whenever the aircraft is not flying flat and level.

The most recent boom-mounted magnetometer system is a variant on the ORAGS-Arrowhead system, known as the ORAGS-VG (Gamey et al., in press). This is a vertical magnetic gradient system in which the eight magnetometers of the Arrowhead system are deployed as four pairs, mounted in pods attached to the Arrowhead side-booms (Figure 4). This system was designed to be more sensitive, allow equivalent acquisition from higher altitudes, and/or provide better isolation of closely-spaced anomalies.

Boom-mounted Electromagnetic Systems

In association with testing and demonstration of the ORAGS-Hammerhead, an electromagnetic prototype, the ORAGS-EMP was constructed and tested (Doll et al., in press). This system uses a modified Geonics EM-61, integrated with the boom structure and recording console of the Hammerhead System. The test of the ORAGS-EMP showed that a boom-mounted electromagnetic system was viable, and led to development of a new time-

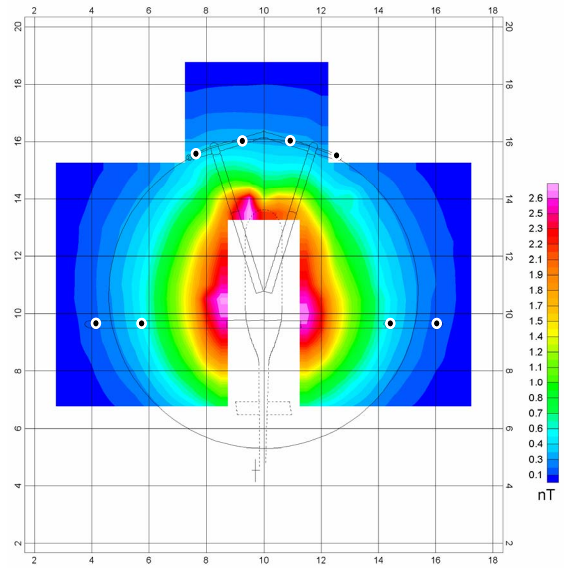

Figure 3. The ORAGS-Arrowhead system. a) photograph of the system in flight, and b) configuration relative to RMS noise.

Figure 4. ORAGS-VG vertical magnetic gradient system.

Figure 5. ORAGS-TEM time-domain electromagnetic system.

domain electromagnetic system (Beard et al., 2004), the ORAGS-TEM (Figure 5). This system has a large 12m by 3m transmitter loop that mounts on a boom frame similar to that of the ORAGS magnetometer systems. It can be used with either a large 2.7m by 2.7m receiver loop, or a smaller 23 cm by 60cm multi-turn coil. Data are sampled at 10,800 Hz, currently for two channels, though more channels will be added soon. The transmitter peak current is typically 30A and it is normally operated at a base frequency of 270 Hz. A 90 Hz base frequency has poorer signal-to-noise properties, but provides better measurements of time constants that can be used to distinguish among different types of metallic objects.

Performance of boom-mounted systems

To date, the ORAGS systems have been deployed at 15 sites in the continental United States. The objective at all but one of these sites has been to use the system for mapping and detection of unexploded ordnance. Two of these surveys used the HM-3 system, four were conducted with the Hammerhead, and nine were flown with the Arrowhead system. Areas as large as 2000 hectares have been surveyed at rates as high as 225 hectares per day at full coverage. The ORAGS-VG and ORAGS-TEM have not been used on any large-scale surveys to date, but each of these two systems has been tested at three Arrowhead sites. At each of the fifteen sites, we have established a test grid for daily quality assurance tests, and to establish the limits of sensitivity for the objects of interest at the site.

At BBR, the test site is more elaborate, consisting of a 105m by 150m grid containing 52 test items. These test items include several types of inert ordnance as well as a number of pipes and other hardware items. It was intended that the test site include some items that would be too small to be detected by some or all of our systems. Some positions in the grid are unoccupied due to natural anomalies, or because they were previously used for surface test objects that were subsequently removed. We will use results from this site as a basis for comparing the different ORAGS systems. Items in the test grid are summarized in Table 1. Their depth of burial, orientation, and length are found in Beard et al., 2004, and other references. The masses of the objects range from less than 1 kg to more than 50 kg, and depth of burial ranges between 0 and 1.3m.

Figure 6 shows results from the BBR test site for the ORAGS-Hammerhead, ORAGS-Arrowhead, ORAGS-VG and one variant of the ORAGS-TEM systems. All data were acquired at a nominal flight altitude of 1.0-1.5m AGL. Results from ground-based instruments show somewhat better sensitivity, as would be expected when the instrument is closer to the ground without helicopter noise.

Table 1. Items buried at the BBR Test Site.

Location	Description	Mass (kg)
Row A		
A1	8 in nail+2 in galv pipe	2.7
A2	3 rebar rods	5.5
A3	2 in galv pipe elbow	4.5
A4	steel channel	6.8
A5	2 in galv pipe	2.7
A6	2 in galv pipe with flanges	4.5
A7	unknown	
A8	box beam	4.5
A9	galv stove pipe	1.8
A10	8 in nail	
Row B		
B1	I beam	13.2
B2	4 rebar rods	4.1
B3	I beam	4.5
B4	250 lb bomb	52
B5	100 lb bomb fragments	unknown
Row C		
C1	100 lb bomb fragments	8.6
C2	250 lb bomb simulant	22.7
C3	250 lb bomb simulant	29
C4	100 lb bomb intact	22.7
C5	100 lb bomb fragments	14.5
C6	2.75 in rocket nose section	4.1
C7	155 mm round	24
C8	105 mm round	8.6
Row D		
D1	100 lb bomb fragments	unknown
D2	100 lb bomb fragments	unknown
D3	2.75 in rocket cylinder	4.1
D4	2.75 in rocket	2.3
D5	105 mm round	8.6
D6	2 2.75 in rocket sim.	5.4
D7	61 mm mortar	0.9
D8	105 mm round	8.6
Row E		
E1	81 mm round	4.1
E2	aluminum rod	0.5
E3	aluminum rod	0.5
E4	aluminum rod	0.5
E5	81 mm round	3.6
E6	81 mm round	3.6
E7	105 mm round	8.2
Row F		
F1	81 mm round	3.2
F2	60 mm illum. round	1.8
F3	60 mm illum. round	1.8
F4	60 mm illum. round	0.9
Row G		
G1	81 mm round	3.2
G2	100 lb bomb	2.7
G3	60 mm mortar round	1.4
G4	2.25 in rocket	4.5
G5	steel pipe	4.1
Row H		
H1	8 in nail	
H2	2.75 in rocket	3.2
H3	155 mm round	25.5
H4	155 mm round	25.5
H5	155 mm round	25.5
H6	8 in nail	

The maps in Figure 6 demonstrate that the airborne systems are able to detect nearly all of the objects in the test site. An incremental improvement can be seen in the magnetometer systems in that several items detected by the Arrowhead system that weren't detected by the Hammerhead system, and further improvements are apparent in the VG system over the total field systems. None of the systems responded to the small aluminum rods (locations E2, E3, and E4). They were apparently too small or linear for the TEM large loop system and would not be expected to be detected by magnetometer systems. One of the aluminum rods was detectable with a high S/N ratio for the small receiver coil TEM system (not shown here). Only the ORAGS-VG showed a response to the 60mm mortar at location G3, and its response is weak and not clear at the scale in Fig. 6. Differences in anomaly amplitude can often be attributed to small differences in altitude during acquisition. Other factors may also explain inconsistencies between TEM amplitudes and magnetometer amplitudes, namely the metallic composition of the target and its shape (which is particularly important for TEM response). In addition, the TEM data may be more responsive to variations in soil properties at this site. At other sites, however, magnetic minerals can interfere with the performance of magnetometer-based systems, and can make them ineffective. At such sites, electromagnetic systems would be preferred. Much of this response has been filtered out of the map in Figure 6d, but some is retained. The ORAGS-VG detects most ferrous targets (some of the 60mm and 81mm are weak and one of the 105mm shells was weak, probably due to altitude on one flight line) and has the best signal-to-noise performance of all systems.

Based on data acquired at the BBR test site with the Arrowhead, VG, and TEM systems, and at many other sites with the Arrowhead system, we have compiled Table 2, which shows the maximum separations (altitude plus depth of burial) for detection of several representative types of UXO. These results demonstrate the higher falloff of amplitude of EM response relative to magnetic response. The vertical gradient system has thresholds that are about two meters higher than the Arrowhead system due to lower noise levels (Gamey et al., in press) and lower sensitivity to small positioning errors (Doll et al., submitted). The amplitude of vertical gradient anomalies decays more rapidly with altitude than an equivalent total field anomaly (Figure 7). However, the noise floor for the vertical gradient anomaly is much lower. Figure 7 shows calculated total field and vertical gradient anomaly peak amplitudes for a representative 100 lb. bomb. Note that the signal and noise floor for the total field measurements cross at about 4.5m, whereas they cross for the vertical gradient at about 6m separation.

Table 2. Estimated altitude thresholds for detection of selected objects listed in Table 1.

Object	Mass (kg)	Arrowhead (*m*)	TEM (*m*)	VG (*m*)
250 *lb* bomb	25-50	12.0	6.0	14.0
100 *lb* bomb	3-23	6.0	5.0	8.0
155 *mm* shell	26	7.0	4.0	9.0
105 *mm* shell	8.5	4.0	3.5	6.0
2.75 *in* rocket	2-4	5.0	3.5	7.0
81 *mm* mortar	3-4	2.5	3.0	4.5
61 *mm* mortar	1	2.0	2.0	4.0

Applications

To date, the ORAGS airborne systems have been used for mapping and detection of UXO (Figure 8). In the process of acquiring data at some survey sites, we have found clear responses to infrastructure and geologic structures (Figure 9). Other appropriate applications might include:

1) mapping of landfills, waste sites, or military installations where the locations of buried metals are not known with sufficient precision.
2) Detailed mapping of surface geology for mineral exploration, fault and fracture mapping, or other uses.

3) Detection of pipelines, abandoned wellheads, or other features of an oil field for purposes of cleanup, or in advance of a three-dimensional seismic survey.
4) Detection of underground storage tanks, cables, or pipelines near airport runways or other sites where it is critical that data be acquired in a time-efficient manner.

Many other environmental and engineering applications can also be considered. The ORAGS systems are designed for operation over land, but can operate in shallow water, such as a surf zone.

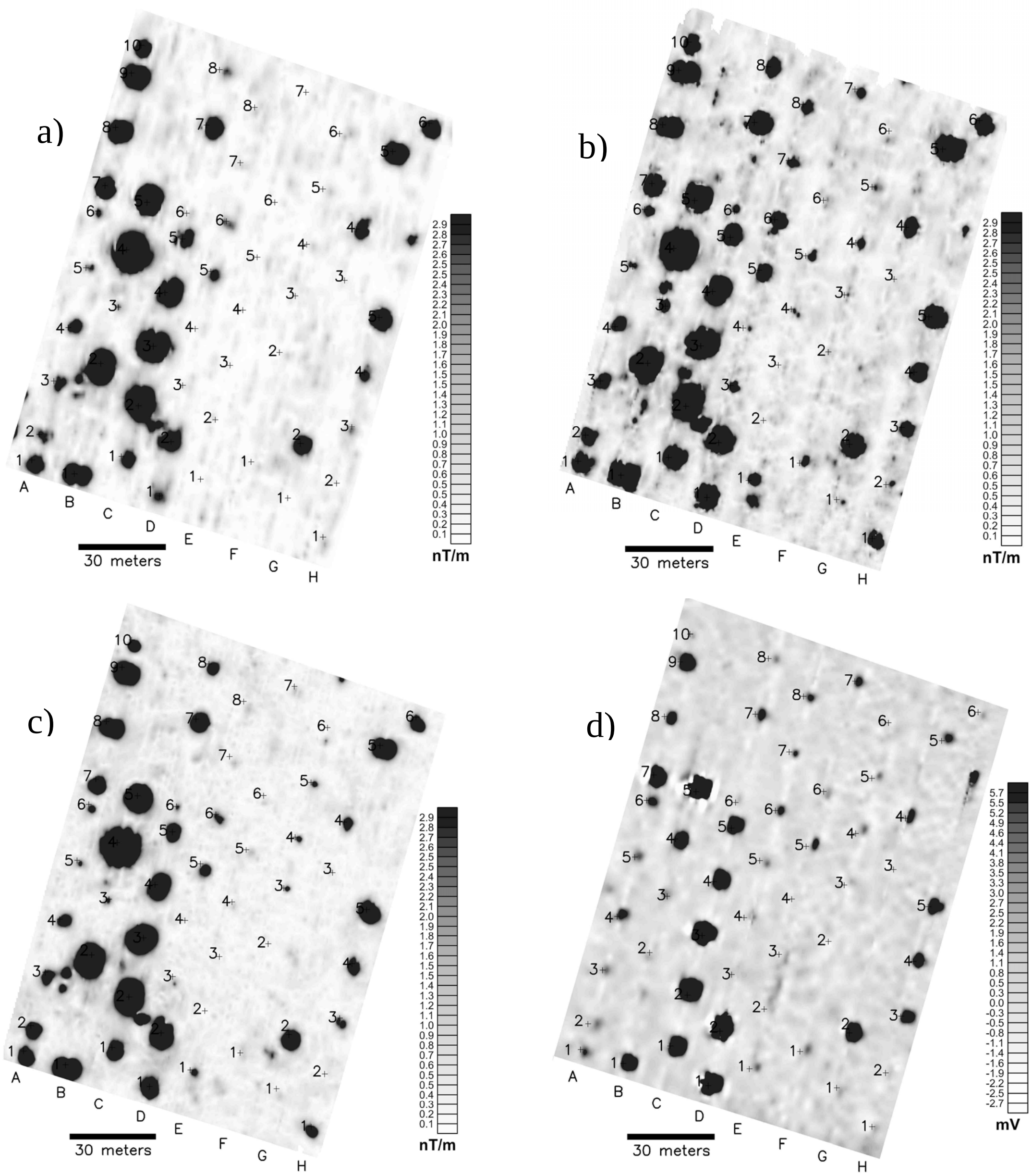

Figure 6. Comparison of results with different ORAGS Systems from the BBR Test Site. Magnetic maps are analytic signal. A) ORAGS Hammerhead, b) ORAGS Arrowhead, c) ORAGS-VG, and d) ORAGS-TEM (large receiver loop variant).

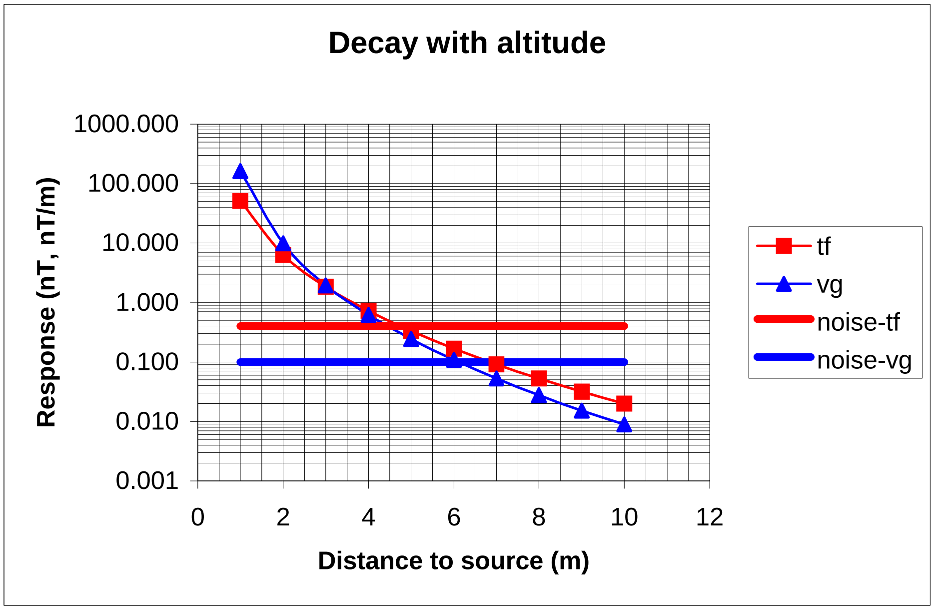

Figure 7. Total field and vertical gradient responses to a dipole source with increasing distance or altitude. A reduction in the noise floor from 0.4nT in the total field to 0.1nT/m in the vertical gradient produces an increase of approximately 1.5m in depth sensitivity. Dipole moment for these curves are consistent with 100 lb. bombs found at BBR. Smaller targets will shift curves downward.

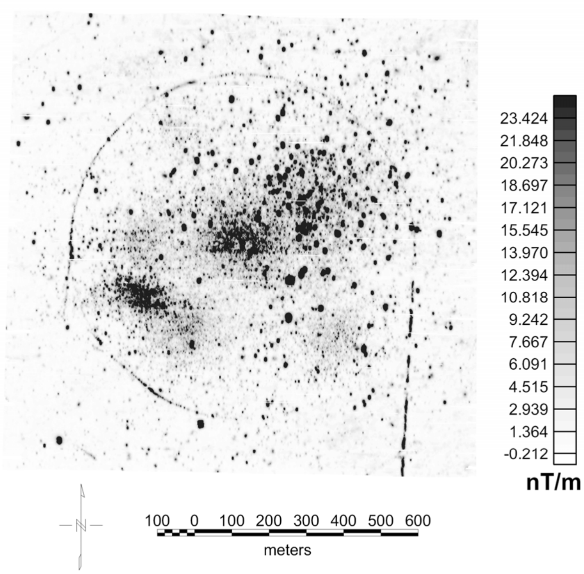

Figure 8. Analytic signal map of a bombing target. Thousands of small anomalies are associated with UXO or metal fragments. A 1km diameter berm of sediment marks the perimeter of the target. A north-trending road is seen in the lower right quadrant of the map, extending to the target berm.

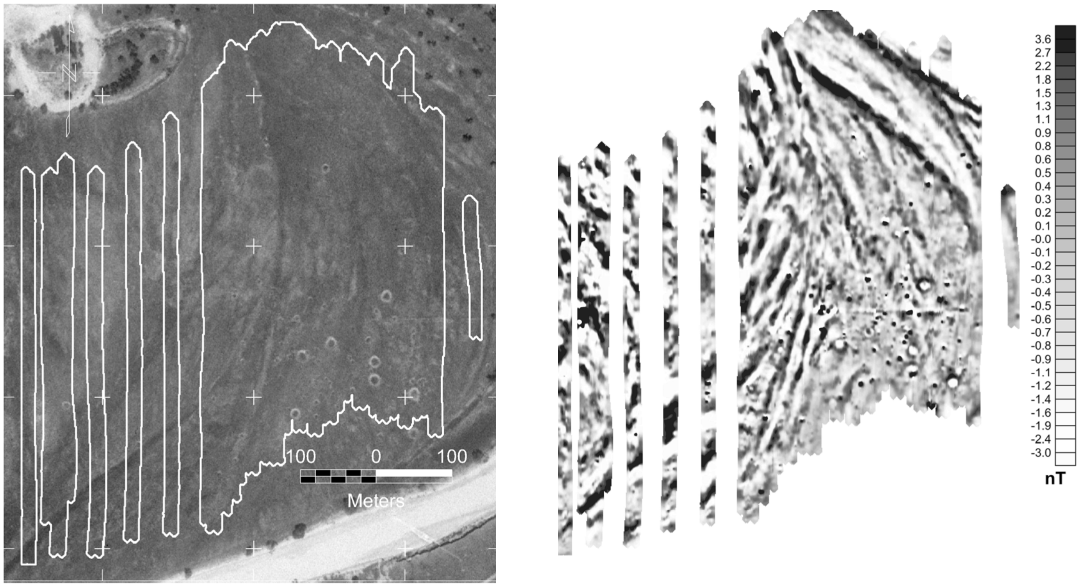

Figure 9. a) Orthophoto map of a meander of the White River, South Dakota; b) ORAGS-Arrowhead total field magnetic map of the area, showing linear magnetic features that are believed to be associated with the distribution of heavy (and often magnetic) minerals in historic stream meanders. Impact craters on the orthophoto map are associated with many of the localized (point-like) magnetic anomalies.

Conclusions

Boom-mounted airborne magnetic and electromagnetic systems have recently been developed for low-altitude airborne surveys, and should be considered for a wide range of problems where it is critical to detect very small targets, or map geologic properties over areas of about 500 hectares and larger. These systems have demonstrated a capability of detection that previously was only possible with man-portable or ground-based vehicle-towed systems.

References

Barringer, A. R., 1990, Historical aspects of airborne electromagnetic development, in Developments and applications of modern airborne electromagnetic surveys, U.S. G. S. Bulletin 1925, D. V. Fitterman, ed., p. 7-8.

Beard, L. P., W. E. Doll, J. S. Holladay, T. J. Gamey, J. L.C. Lee, and D. T. Bell, 2004, Field tests of an experimental helicopter time-domain electromagnetic system for unexploded ordnance detection, *Geophysics*, v. 69, n. 3.

Doll, W. E., P. Hamlett, J. Smyre, J. E. Nyquist, T. J. Gamey, and J. S. Holladay, 1999, A field evaluation of airborne techniques for detection of unexploded ordnance, abstract, *Proceedings of the 1999 Symposium on the Application of Geophysics to Environmental and Engineering Problems*, p. 773-782.

Doll, W. E., J. E. Nyquist, L.P. Beard, and T. J. Gamey, 2000. Airborne geophysical surveying for hazardous waste site characterization on the Oak Ridge Reservation, Tennessee, *Geophysics*, v. 65, n. 5, p. 1372-1387.

Boom-mounted Airborne Geophysical Systems

Doll, W. E., T. J. Gamey, L. P. Beard, D. T. Bell, and J. S. Holladay, 2003, Recent advances in airborne survey technology yield performance approaching ground-based Ssurveys, *The Leading Edge*, Soc. Expl. Geophysicists, p. 420-425, v. 22, n. 5, May 2003.

Doll, W. E., T. J. Gamey, J. S. Holladay, and J.L.C. Lee, in press, Viability of an airborne electromagnetic system for mapping of shallow buried metals, accepted for publication in *Near-Surface Geophysics: Volume 2, Applications and Case Histories,* Dwain K. Butler (Ed.), Soc. Expl. Geoph., to be published in 2004.

Doll, W. E., T. J. Gamey, L. P. Beard, A.M. Emond, D.T. Bell, submitted, Comparison of airborne vertical magnetic gradient and total field products for mapping and detection of UXO and ferrous wastes, Extended Abstract, submitted to the 2004 Annual Meeting of the Soc. Expl. Geophysicists, 4 pp.

Gamey, T. J., W. E. Doll, D. T. Bell, A. Duffy, and S. D. Millhouse, 2000, Evaluation of improved airborne techniques for detection of UXO, , extended abstract, *Proceedings of the 2000 Symposium on the Application of Geophysics to Environmental and Engineering Problems*, p. 57-66.

Gamey, T. J., W. E. Doll, L. P. Beard, and D. T. Bell, in press, Analysis of correlated noise in airborne magnetic gradients for UXO detection, , accepted for publication in *Jour. Env. and Eng. Geophysics.*

Hildenbrand, T. G., G. L. Raines, and D. V. Fitterman, 1990, National airborne geophysics program, in Developments and applications of modern airborne electromagnetic surveys, U.S.G. S. Bulletin 1925, D. V. Fitterman, ed., p. 3-5.

Paine, J. G., 2003, Workshop notes: Airborne geophysics: Applications and advances in environmental and engineering investigations, Env. and Eng. Geophysical Society, Denver, CO, April 2003, p. 1.

Pellerin, L., and V. Labson, 2003, An empirical approach to inversion of an unconventional helicopter electromagnetic dataset, J. Appl. Geoph., v. 53, n. 1, p. 49-61.

Acknowledgements

This work was funded by the Environmental Security Technology Certification Program, under the direction of Dr. Anne Andrews and Dr. Jeffrey Marquesee. Oak Ridge National Laboratory is managed by UT-Battelle, LLC for the U. S. Department of Energy under contract DE-AC05-00OR22725. The submitted manuscript has been authored by a contractor of the U. S. Government. 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.