INNOVATIVE TECHNOLOGY
Summary Report

DOE/EM-0502

Magnetometer Towed Array

Subsurface Contaminants Focus Area

Prepared for
U.S. Department of Energy
Office of Environmental Management
Office of Science and Technology

September 1999

INNOVATIVE TECHNOLOGY
Summary Report

Magnetometer Towed Array

OST/TMS ID 548

Subsurface Contaminants Focus Area

Demonstrated at
Los Alamos National Laboratory
Los Alamos, New Mexico
and
Kirtland Air Force Base
Albuquerque, New Mexico

Innovative Technology
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at http://ost.em.doe.gov under "Publications."

TABLE OF CONTENTS

APPENDICES

SECTION 1

SUMMARY

Technology Summary

Problem

The assessment of buried wastes requires collecting site-specific data to determine the location and level of contamination. These data can be obtained by using both intrusive and non-intrusive methods. While intrusive methods, such as boreholes, provide direct information about the subsurface, they can result in greater risks to on-site workers, may be slow, provide only point measurements, and are costly. Non-intrusive methods, such as magnetometers, provide information that can be used to infer subsurface conditions. These methods result in less risk to site workers, are typically rapid, can be used to measure larger areas, and are relatively inexpensive. They are excellent for Phase I screening of a site.

How It Works

- The Magnetometer Towed Array is a passive, non-intrusive, site-assessment method used to infer subsurface conditions at sites where buried waste are contained or encapsulated in ferromagnetic materials.
- The Magnetometer Towed Array is designed to collect a high number of survey points with accurately referenced latitude and longitude over a large area in a short period of time with near real-time data interpretation.
- The Magnetometer Towed Array is a vehicle-based system (see Figure 1) that measures the strength of the earth's magnetic field while traveling at speeds of 5 to 15 miles per hour (mph).

Figure 1. Photograph of the Magnetometer Towed Array vehicle

— Buried objects are identified by a change in the earth's normal magnetic field. The earth's magnetic field is measured by seven cesium vapor magnetometers that are mounted on a 10-ft-wide boom on the towed platform. Each magnetometer takes 20 measurements/second. This rate provides 70,000 measurements/acre (at 5 mph) or one measurement for every $1.5 ft^2$.

- — The measurement data are then automatically processed by the system computers to provide high-resolution maps that show the latitude and longitude of buried ferrous objects.
- — A differential global positioning system (DGPS) was integrated into the system to provide high-accuracy location control.

Additionally, magnetic characteristics are collected and used to estimate the depth to and size of the objects detected.

Potential Markets

The Magnetometer Towed Array can be used at all buried waste sites where wastes were disposed in ferromagnetic materials. These sites could be owned by Department of Energy, Department of Defense, commercial sites, and others.

Advantages Over Baseline

- The Magnetometer Towed Array surveys 15 acres/day in contrast to 2 acres/day using a conventional magnetometer. The technology is more cost effective on a site larger than 50 acres when compared with conventional techniques on a 5-ft grid. When high-density sampling is necessary (less than 2-ft grid spacing), the Magnetometer Towed Array is more cost effective than conventional techniques at sites greater than 3 acres.
- The high data-collection density allows better horizontal resolution and is more likely to identify buried ferrous objects. For example, the boundaries of burials cannot be estimated accurately using data collected on 10-ft centers.
- A finer grid provides data redundancy; thus, a single erroneous data point can be recognized, whereas a survey on 5 of 10 centers may be impossible to recognize an erroneous data point.
- Data collected on a fine grid can be quantitatively interpreted (size and location) using computer algorithms; such analysis is not meaningful when applied to conventional low-density data.

Demonstration Summary

- The Magnetometer Towed Array, also called the Surface Towed Ordnance Locator System (STOLS™) was built by the U. S. Navy as a proof-of-principal, non-intrusive characterization system to locate and identify buried ordnance.
- Under the U. S. Department of Energy (DOE) Mixed Waste Landfill Demonstration Program, Sandia National Laboratories (Sandia), in conjunction with the U. S. Naval Research Laboratory (NRL) and Geo-Centers, Inc., demonstrated and enhanced a commercially available system that was also suitable for use in characterization of DOE waste disposal sites. The development began in 1991; the relationship between Sandia and NRL ended in 1994.
- The DOE/NRL team efforts focused on developing a more accurate and reliable global positioning system (GPS) and software enhancements that made the graphic display more versatile and user friendly. Concurrently, Geo-Centers, Inc. redesigned and built a commercially-viable tow vehicle and tow platform.
- NRL has pursued further refinements in the magnetometer sensor technology and has worked to integrate other non-intrusive survey methods (such as ground-penetrating radar) into the towed vehicle-type system.
- Sandia was responsible for managing the team that adapted the Magnetometer Towed Array for use at hazardous and radioactive waste sites and worked to select appropriate demonstration sites. Sandia National Laboratories' Technical Area-2 (TA-2), Albuquerque, New Mexico served as the initial test site. Demonstrations also occurred at the Radioactive Burial-11 (RB-11) site at Kirtland Air Force Base, Albuquerque, New Mexico; TA-50 Material Disposal Area C at the Los Alamos National Laboratory, Los Alamos, New Mexico; and Technical Area-73 (TA-73) at the Los Alamos Airport landfill (TA-73 results are not presented in this document).

- NRL's Chesapeake Beach Detachment, Chesapeake Beach, Maryland, site was used to test and select the new GPS that replaced the microwave-based GPS that was deficient during early survey work at TA-2. As a result of the NRL support to the project, a Trimble Navigation 4000 SSE DGPS was selected and integrated into the Magnetometer Towed Array; it is capable of accuracy within a meter while traveling at 5 mph.
- The Magnetometer Towed Array demonstrations were successful. The objectives for the site surveys were met. The surveys provide high-quality magnetic maps of the surveyed areas. In addition, magnetic data characteristic of anomalous objects were used to draw conclusions concerning size and depth of burial sites.
- The Magnetometer Towed Array is marketed by Geo-Centers, Inc., as the STOLS™ Search Technologies, Inc. (STI). Services are sold primarily to the Department of Defense.

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Other

All published Innovative Technology Summary Reports are available on the OST Web site at http://em-50.em.doe.gov under "Publications." The Technology Management System, also available through the OST Web site, provides information about OST programs, technologies, and problems. The OST Reference # for Magnetometer Towed Array is 548.

SECTION 2

TECHNOLOGY DESCRIPTION

Overall Product Definition

The vehicle-based system deploys a passive, non-intrusive sensor platform containing seven total-field magnetometers positioned by differential global positioning navigation technology. The components of the system are described in the following section. Figure 2 is the system schematic.

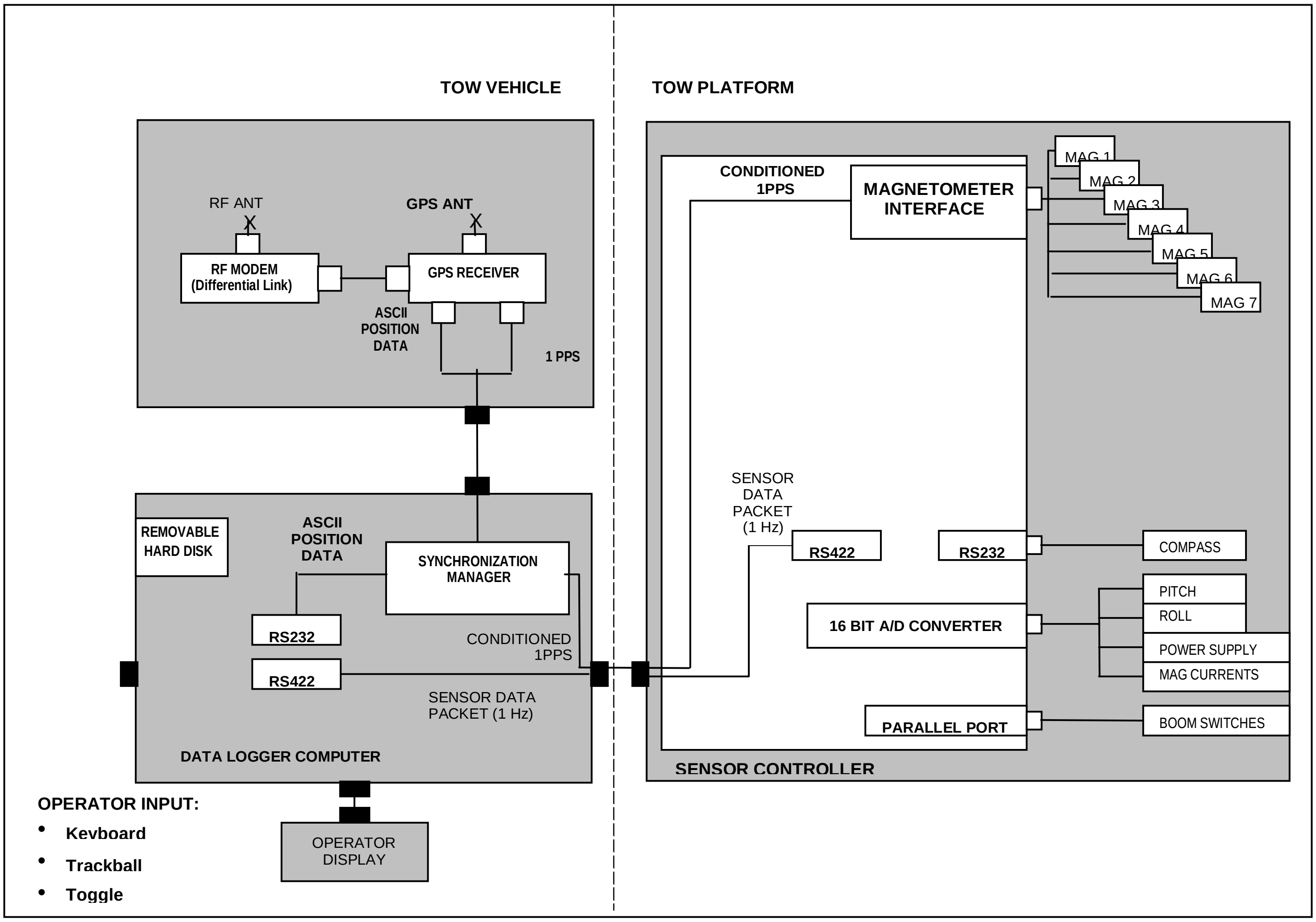

Figure 2. Schematic of Magnetometer Towed Array System

- An important aspect of the Magnetometer Towed Array design is the tow vehicle and towed platform. It was designed to minimize magnetic self-signature and to maximize off-road mobility. The specifications are as follows.
  - — The tow vehicle has a minimum of clearance of 14 in and a shock travel of 12 in. The wheel track is 78 in, and the wheel base is 110 in.
  - — An aluminum chassis/body/wheels and magnesium engine block have been incorporated to reduce the vehicle magnetic signature. The total ferrous mass has been minimized.
  - — The vehicle has two forward gears and reverse and is designed to travel between 5 and 15 mph. The normal speed at which a survey is conducted is 7 mph.

- The towed platform is connected to the tow vehicle by a 10-ft tow bar.
- The towed platform is made exclusively of nonmagnetic materials, including aircraft-grade aluminum, bronze, and titanium.
- Nonmagnetic gas springs provide independent suspension with 6 in of wheel travel.
- The front wheels are allowed 60^{o} excursion to either side.
- The running clearance is 18 in, and the width is 72 in, allowing the towed platform to traverse any terrain that a tow vehicle traverses.
- The magnetometers are mounted at 1⅛-m intervals on a 10-ft boom that is enclosed in a composite shield and rides on a mechanism that folds into the platform if an obstruction is encountered. The same mechanism allows the magnetometers to be adjusted from 6 to 18 in off the ground.

- The Magnetometer Towed Array design has incorporated seven Geometrics 822 cesium-vapor, optically-pumped, total-field magnetometers into the towed platform and one magnetometer at a fixed location not influenced by buried objects. The fixed-location magnetometer is used to correct for changes in the earth's magnetic field that occur during the survey. The sensors produce an analog signal proportional to the magnetic field that is fed to the sensor control computer.
- In addition to the magnetometers, the towed platform also includes a power supply, compass, pitch-and-roll inclinometer, and the sensor-control computer.
- The navigation system uses a DGPS. One of the DGPS receivers is at the tow vehicle and another receiver is at a fixed location of known coordinates. Both receivers record location data from four satellites. The fixed location is used to correct satellite signal noise. The accuracy of the DGPS is within 1 m while traveling at 5 mph. Subsequent data processing allows accuracy to the decimeter level.
- The data logger computer is also located on the tow vehicle. It receives data from the DGPS and the sensor control computer and is used to process the data. The data logger computer includes a monitor and keyboard.
- For sites that are not vehicle accessible, a two-magnetometer, man-portable system that inputs data to the vehicle-based system is used.

System Operation

The premise of the system is that earth generates a magnetic field. The earth's magnetic field lines are just like those produced by a bar magnet under a piece of paper with iron filings on it. The iron filings orient with the magnetic field lines of the bar magnet in the same way a magnetometer shows the earth's magnetic field lines. Field lines are measured in terms of direction and strength. At the equator, the field lines would be parallel to the earth's surface and the field strength would be the weakest. At the pole of the earth, the field lines would be perpendicular to the earth's surface and the field strength would be the strongest. Ferromagnetic objects (i. e., objects attracted by a magnet) cause changes to the earth's normal field lines. The forces of attraction between a magnet and a ferromagnetic object are the same as those observed with buried objects and the earth's magnetic field. The degree to which the earth's field lines change is related to the type of material, size, and distance. For a given object, the field strength decays as the inverse cube of the distance.

- The Magnetometer Towed Array measures the strength of the magnetic field at each of the seven magnetometers on the towed platform and at the fixed-location magnetometer, which is used to measure normal fluctuations in the earth's magnetic field. The time and frequency of readings taken from the magnetometer on the towed platform and the fixed location are synchronized so that the reading from the fixed location can be subtracted from the readings from the towed platform. Therefore, only ferromagnetic anomalies in the surveyed area result in changes in the field strength measured by the magnetometers.
- Because the magnetometers are also sensitive to orientation and the equipment power supply, the sensor control computer also receives input signals from the compass, pitch-and-roll inclinometer, and the power supply. These signals are also used to correct the magnetometer readings.

- Each magnetometer takes 20 measurements/s. This rate provides 70,000 measurements/acre (at 5 mph) or one measurement for every 1.5 ft^2. Data from the sensor control computer are transmitted to the data logging computer, where data from the DGPS are also logged.
- When data are processed, a gray scale (or color) magnetic map is produced. Because of the high density of points produced, the map appears to be continuous. Buried ferromagnetic objects appear as a contrasting lighter or darker color. Figure 3, a photograph of the display screen, illustrates typical results. The map produced is available on the same day as the survey.

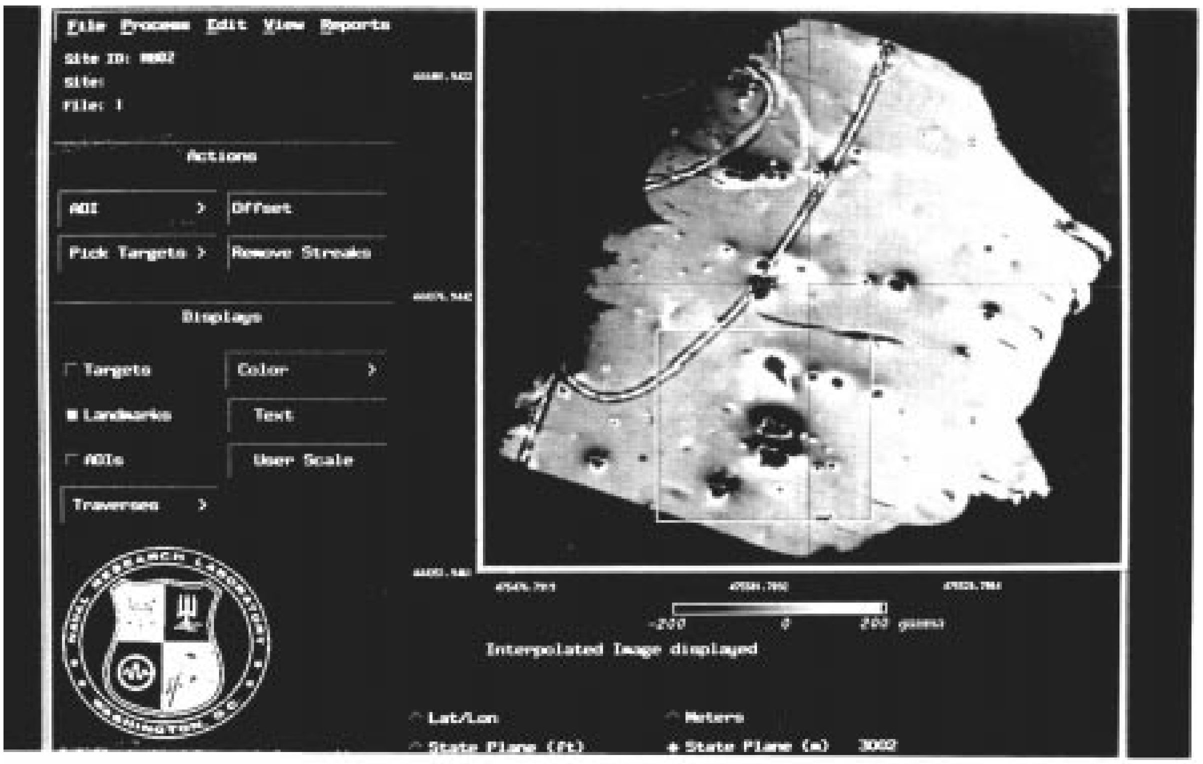

Figure 3. Photo of monitor screen displaying map produced from measurements transmitted from the Magnetometer Towed Array

- Using the magnetic map to select the anomalous area, the operator is then able to perform additional data interpretation that provides information of the size and depth of the object (left side of screen, Figure 3). The unknown object is assumed to fit a dipole mathematical model. An iterative least-squares algorithm is used to match the field data to the dipole model solution that best represents the object size and depth. Figure 4 compares the dipole model with a single field-measured 55-gal drum. The model provides a reasonable fit for single objects and is the method now used by Geo-Centers, Inc.
- While conducting the survey, the operator can take the navigation system antenna and hold it over a landmark and create a reference point in the data set.

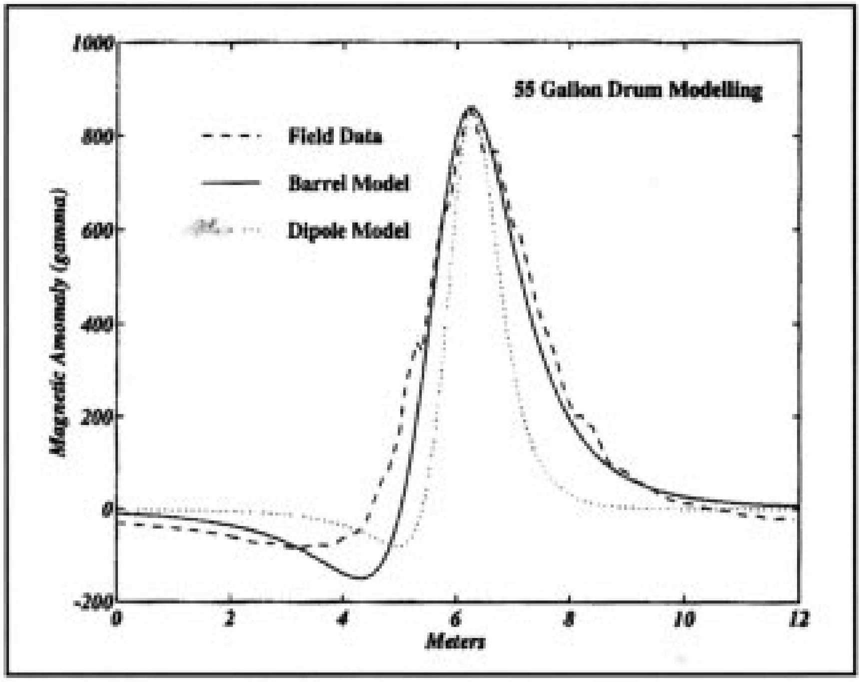

Figure 4. A comparison of field data collected 1.1 m above a barrel to a point dipole model and a barrel model

SECTION 3

PERFORMANCE

Demonstration Plan

Results of two demonstrations, one at the Kirtland Air Force Base in Albuquerque New Mexico (RB-11) and one at the Los Alamos National Laboratory (MDA-C) are presented in this report. The plan for each is presented in this subsection and the results of each are then presented in the next subsection.

Kirtland Air Force Base RB-11 Site

- RB-11 is a 4.5-acre landfill used from 1960 to 1971 and is described as containing nine trenches. The trenches were believed to be oriented east-west and range from 8 to 20 ft deep with 3 ft of cover. Much of the waste was believed to be contained in steel 55-gal drums. No known fences or utilities are on the site. The site contains mixed waste.
- The objectives of the RB-11 demonstration included the following:
  - To determine the exact location of the trenches;
  - To demonstrate the reliability of the newly integrated DGPS;
  - To test the upgraded hardware and software; and
  - To evaluate the mobility of the designed tow vehicle and towed platform.
- Included in the survey was an area prepared with known steel object configurations that would be used to confirm the accuracy of the survey results.
- Survey data could be compared with a 1988 conventional magnetometer survey that was conducted on a 10 by 10-ft grid.

Figure 5 shows the survey area at RB-11. The points RB-11 #1 to RB-11 #7 show the boundary of the area. The lines marked T-1 to T-10 are the positions of the disposal areas based on historic data, aerial photographs, and previous site surveys.

Los Alamos National Laboratory MDA C Site

- MDA C covers 12 acres and contains 6 large trenches, a chemical disposal pit, and 108 disposal shafts. The landfill was used from 1948 to 1974. The trenches are 500 to 800 ft long, 40 to 100 ft wide, and about 20 ft deep. The chemical pit is estimated to be 180 ft long, 25 ft wide, and 12 ft deep. The disposal shafts are up to 2 ft in diameter and up to 25 ft deep. Disposal of radioactive waste as well as various hazardous metals were disposed at the site. To control the spread of contamination, between 0.5 and 3 ft of soil was spread over the site in 1984.
- The objectives of the MDA C demonstration, conducted in 1994, included the following:
  - To determine the exact location of the disposal pits and shafts;
  - To demonstrate the reliability of the newly integrated DGPS;
  - To test the upgraded hardware and software reliability of the detection and data analysis instrumentation and computers; and
  - To evaluate the mobility of the redesigned tow vehicle and towed platform.
- The disposal shafts at this site provided a special testing scenario for the high-density survey capability of the Magnetometer Towed Array.

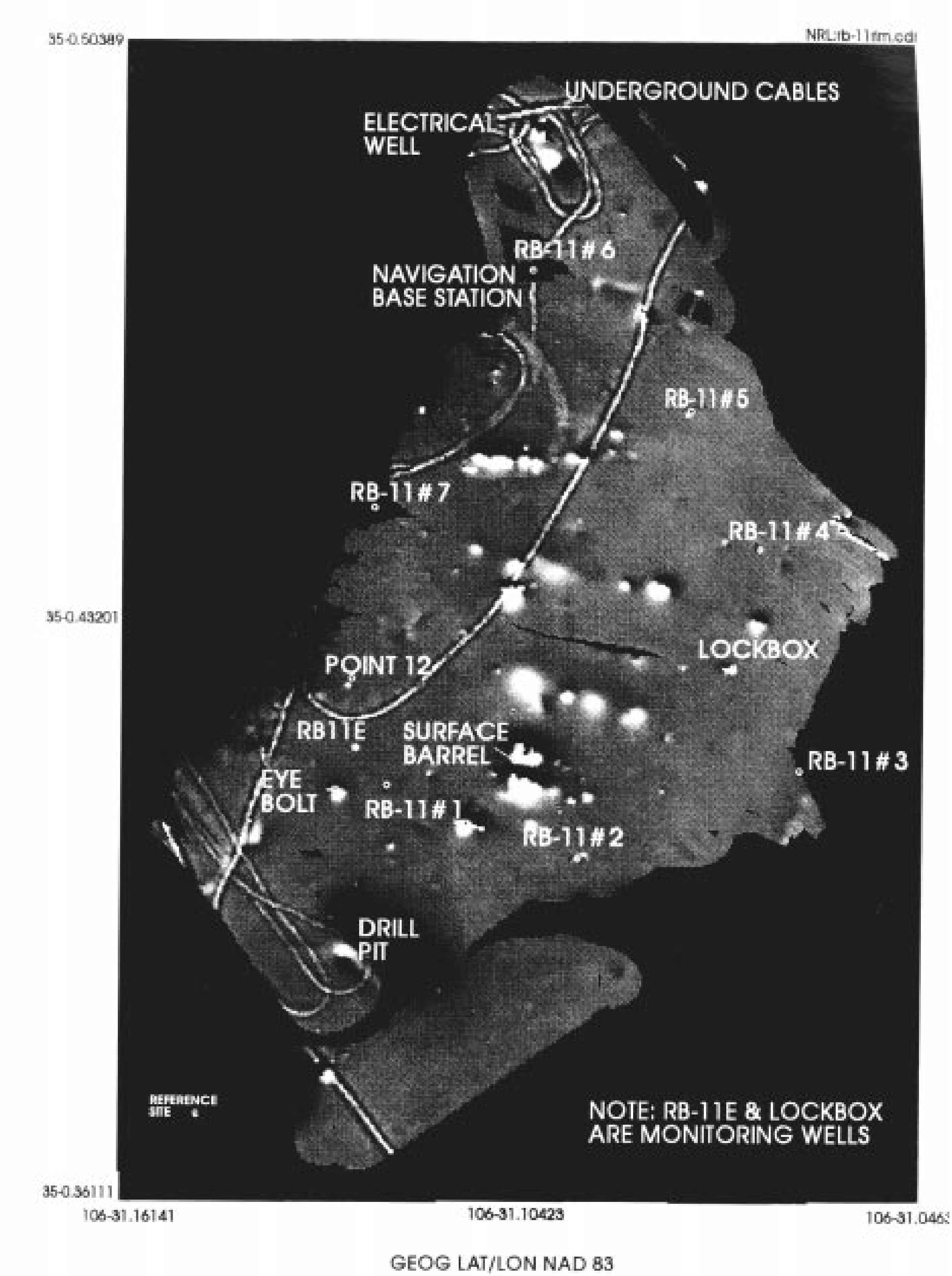

Figure 5. Surveyed area at RB-11

Performance

Kirtland Air Force Base RB-11 Site

- The demonstration met the objectives of the survey. The high-density survey provided new and better definition of the trench boundaries and the identification and location of undocumented large power cables cutting through the site. The 4.5-acre site was surveyed in less than 2 hrs.
- Figure 6 shows the gray-scale map of the anomalies overlaid with the data interpretation of trench locations (outlined in white boxes). The boundary of the burial area in shown with a black line. Trenches “A” to “H” correspond to propose location of trenches T-1 to T-10 shown on Figure 5. The survey showed that trenches T-9 and T-10 are indistinguishable.

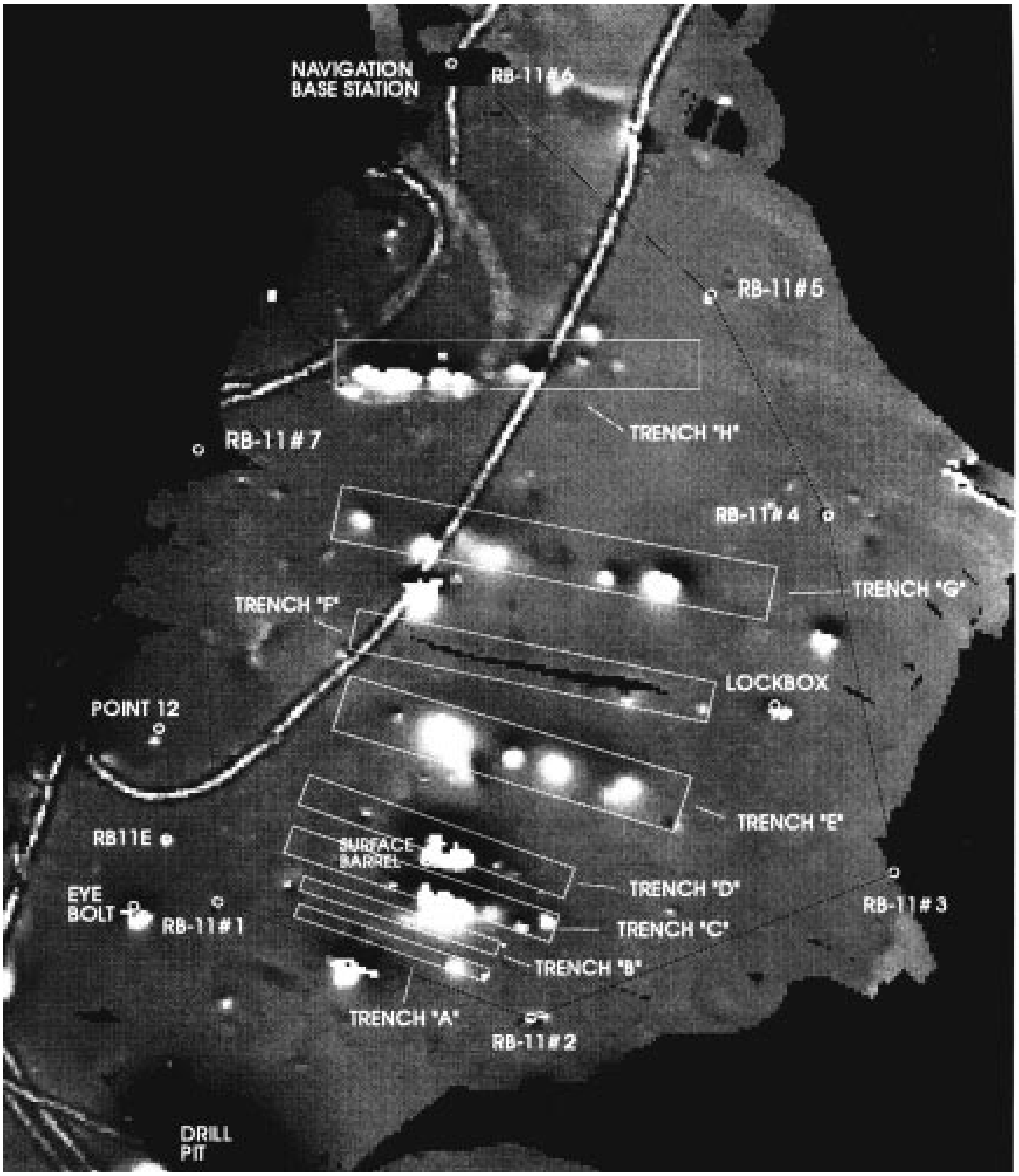

Figure 6. Gray-scale map of anomalies at RB-11 using Magnetometer Towed Array

- When compared with the low-density survey (Figure 7), the resolution of the trenches is much clearer.

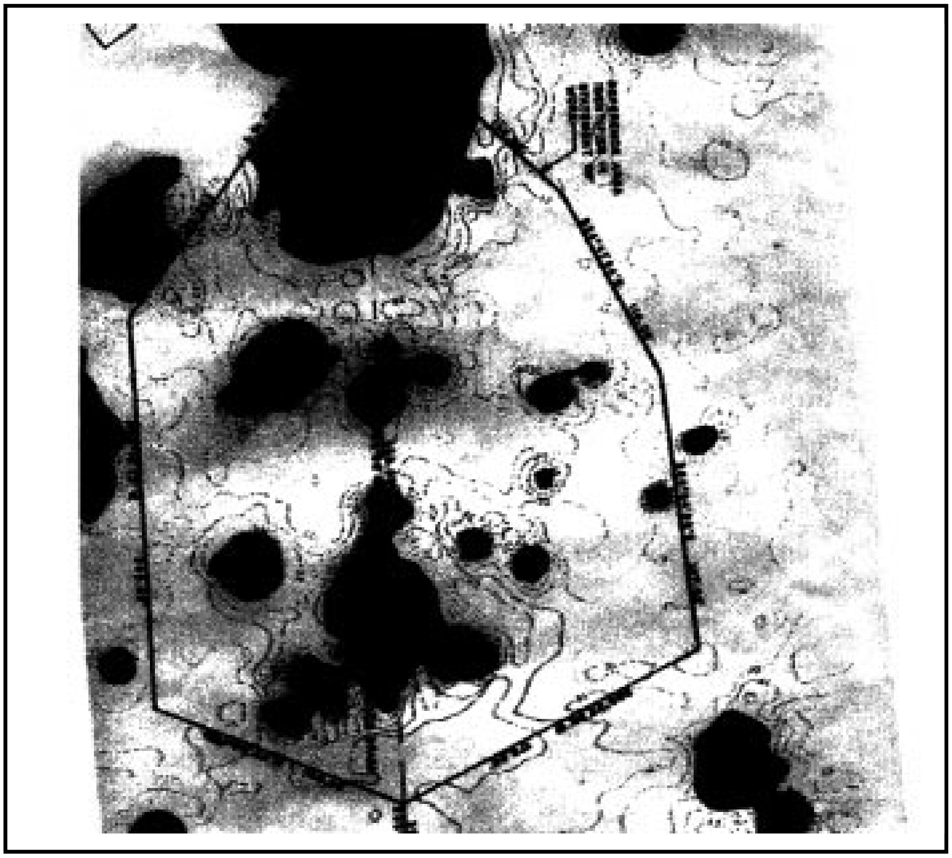

Figure 7. Low-density, 10-ft grid spacing survey at RB-11 performed using tradition survey techniques

Los Alamos National Laboratory MDA C Site

- The demonstration conducted at MDA C was successful in defining the location of the trenches (Figure 8). Black lines represent the new understanding of the size of the trenches from this survey. Some of the shafts at the site were also identified. Interferences from the trenches made it impossible to resolve other shafts.
- In some part of MDA C, the slope of the land resulted in a dead zone for the detectors. More development work was thought necessary for resolution of this rare occurrence.

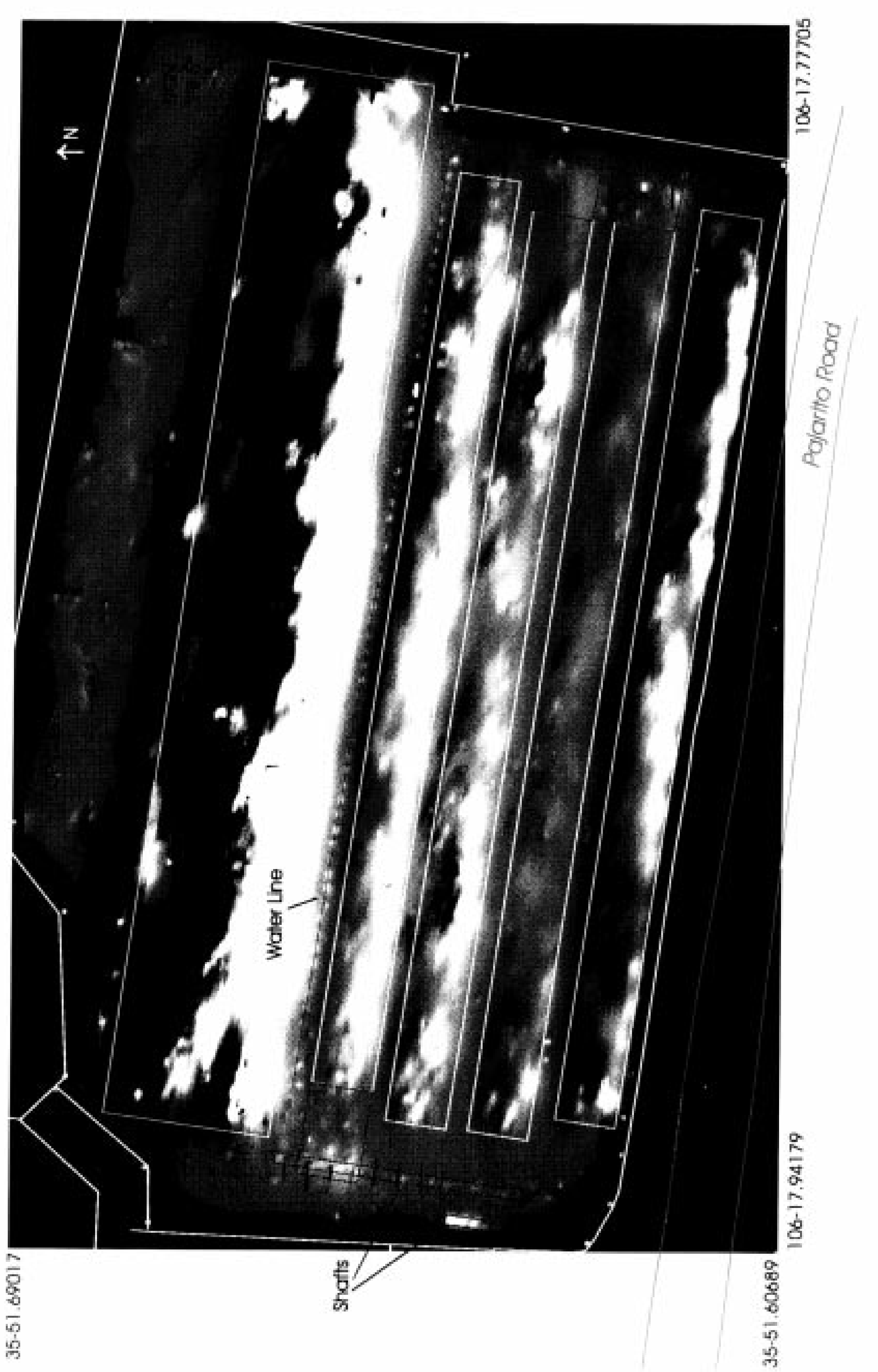

Figure 8. MDA C report results

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Competing Technologies

- The Magnetometer Towed Array competes with a conventional magnetometer. The conventional survey approach is as follows:
  - — the position of the corners of the grid are established by surveying;
  - — the survey grid is laid out at the desired density (usually 5 ft by 5 ft spacing);
  - — a person carrying a hand-held magnetometer walks the grid, taking measurements at grid intersections;
  - — the measurements are logged for later data interpretation; and
  - — data are then fed to a contouring program, which is used to produce a contour map of the data.
- The Magnetometer Towed Array also competes with other non-intrusive survey instrumentation such as ground-penetrating radar or electromagnetic induction (e. g., EM-61).
- Improvements can be added to the traditional survey methodologies. Automated site positioning systems that allow correlation of sensor data to positioning data have been added to various systems, and data can be collected at a given frequency. Computer software improvements have allowed automation of the anomaly mapping procedure. The drawback to traditional techniques is that all of the equipment must be carried, pulled, or pushed by the survey technician.
- At the time of the demonstrations, the Magnetometer Towed Array was the only system that collected data at high speeds and allowed the operator to see the magnetic maps as the data were collected, thus allowing survey adjustments as needed to capture larger areas or to adjust the instrument configuration to optimize data quality.

Technology Applicability

- A large number of DOE Environmental Restoration (ER) Program waste sites involve the assessment and cleanup of buried wastes. As of 1990 landfills within the DOE complex were estimated to contain 3 million cubic meters of buried waste. All DOE sites have these types of facilities. The DOE sites containing the largest volumes of buried waste include Hanford, Savannah River Site, Idaho National Engineering and Environmental Laboratory, Los Alamos National Laboratory, Oak Ridge Reservation, Nevada Test Site, and Rocky Flats Environmental Technology Site.
- The Magnetometer Towed Array is a passive, non-intrusive, site-assessment method used to infer subsurface conditions at sites where buried waste contain or are encapsulated in ferromagnetic materials. Passive methods have only a receiver, whereas active methods have a transmitter and a receiver.
- The Magnetometer Towed Array is designed to collect a high number of survey points with accurately referenced latitude and longitude over a large area in a short period of time with near teal-time data interpretation
- The Magnetometer Towed Array is best suited to sites or multiple sites that encompass a large (50 acres) area to be surveyed or requiring a dense grid spacing (2 by 2 on at a typical 10-acre site).

Patents/Commercialization/Sponsor

Magnetometer Towed Array is commercially available as the STOLS ™ Search Technologies, Inc. (STI) system, sold by Geo-Centers, Inc..

SECTION 5

COST

Methodology

- The cost analysis presented herein is based on the cost-effectiveness report prepared by the Los Alamos National Laboratory.
- Cost for the Magnetometer Towed Array is provided as a per-acre price quote from Geo-Centers, Inc.
  - Included is the mobilization cost, one-day drive for the Magnetometer Towed Array, or $100 airfare for only the man-held unit.
  - Landmark mapping is not included.
  - Costs were provided for both ideal conditions (vehicle travel rate of 8 to 10 mph) and non-ideal conditions (3 to 5 mph).
- Conventional technology costs were developed for an in-house scenario where the equipment is purchased and operated by fully burdened employees. The bases are outlined as follows:
  - The purchase price of all the necessary equipment, software, and supplies was acquired and amortized over a 5-year period to establish a daily rate.
  - An estimate of the productivity rate of the staff was generated and used to establish how much effort and time was involved to conduct an acre survey under different worker-protection requirements (Level C or Level D) and grid-spacing requirements.
  - Based on different labor rates, a site acreage table was put together to present the cost per acre versus site size.
- The cost estimates for conventional technology were also developed from a survey of contractors selling conventional surveys. This pricing was similar to the in-house scenario and validated that approach.
- The costs for the Magnetometer Towed Array were compared with the conventional approach, and tables were developed showing the optimum cost effectiveness.

Cost Analysis

Table 1 shows the Magnetometer Towed Array pricing per acre provided by Geo-Centers, Inc. It includes both the ideal survey conducted at 8 to 10 mph and the non-ideal survey conducted at 3 to 5 mph.

- Tables 2 through 5 present a cost comparison of the Magnetometer Towed Array and conventional technology. Magnetometer Towed Array pricing is using a fixed labor rate. The conventional technology burden rate for labor varies for different areas of the country; thus, the tables contain different burden rates. The difference in price per acre between Magnetometer Towed Array and conventional technology is presented in the tables.

Table 1. Magnetometer Towed Array survey cost (per acre)

	Ideal Site Conditions					
	Level D			Level C		
Acres	Towed	Man-Portable	Most Cost Effective	Towed	Man-Portable	Most Cost Effective
2		$7,525	$7,525		$8,585	$8,585
5		$4,202	$4,202		$5,553	$5,553
10	$5,146	$2,808	$2,808	$6,689	$4,342	$4,342
50	$1,329		$1,329	$1,644		$1,644
100	$942		$942	$1,127		$1,127
500	$567		$567	$593		$593
1000	$507		$507	$535		$535

	Non-Ideal Site Conditions					
	Level D			Level C		
Acres	Towed	Man-Portable	Most Cost Effective	Towed	Man-Portable	Most Cost Effective
2		$7,525	$7,525		$10,435	$10,435
5		$4,785	$4,785		$7,116	$7,116
10	$5,146	$3,433	$3,433	$6,689	$6,233	$6,233
50	$1,792		$1,792	$2,121		$2,121
100	$1,416		$1,416	$1,615		$1,615
500	$1,115		$1,115	$1,174		$1,174
1000	$1,055		$1,055	$1,097		$1,097

Table 2. Cost comparison (5-ft centers), ideal site. (Negative numbers represent added cost for the Magnetometer Towed Array)

Ideal Site Savings per Acre – Level D Typical Fully Burdened Labor Rates	$40	$50	$60	$70	$80
Acres					
2	**($6,297)**	**($6,023)**	**($5,750)**	**($5,477)**	**($5,203)**
5	**($3,166)**	**($2,940)**	**($2,715)**	**($2,490)**	**($2,264)**
10	**($1,836)**	**($1,626)**	**($1,417)**	**($1,208)**	**($ 998)**
50	**($408)**	**($211)**	**($15)**	**$182**	**$378**
100	**($27)**	**$168**	**$362**	**$557**	**$752**
500	**$343**	**$536**	**$730**	**$923**	**$1,117**
1000	**$402**	**$595**	**$789**	**$982**	**$1,176**
Savings per Acre – Level C					
Acres					
2	**($6,519)**	**($6,052)**	**($5,585)**	**($5,119)**	**($4,652)**
5	**($3,679)**	**($3,260)**	**($2,841)**	**($2,423)**	**($2,004)**
10	**($2,532)**	**($2,129)**	**($1,726)**	**($1,324)**	**($921)**
50	**$115**	**$505**	**$895**	**$1,285**	**$1,675**
100	**$626**	**$1,014**	**$1,402**	**$1,791**	**$2,179**
500	**$1,155**	**$1,542**	**$1,929**	**$2,316**	**$2,703**
1000	**$1,212**	**$1,599**	**$1,986**	**$2,373**	**$2,759**

Table 3. Cost comparison (2-ft centers), ideal site

Ideal Site Savings per Acre – Level D Typical Fully Burdened Labor Rates Acres	$40	$50	$60	$70	$80
2	($3,091)	($2,100)	($1,109)	($119)	$872
5	$40	$983	$1,926	$2,868	$3,811
10	$1,370	$2,297	$3,224	$4,150	$5,077
50	$2,798	$3,712	$4,626	$5,540	$6,453
100	$3,179	$4,091	$5,003	$5,915	$6,828
500	$3,549	$4,459	$5,370	$6,281	$7,192
1000	$3,608	$4,519	$5,430	$6,340	$7,251
Savings per Acre – Level C					
Acres					
2	($107)	$1,795	$3,696	$5,597	$7,499
5	$2,733	$4,587	$6,440	$8,293	$10,147
10	$3,880	$5,718	$7,555	$9,392	$11,230
50	$6,527	$8,352	$10,176	$12,001	$13,825
100	$7,038	$8,861	$10,684	$12,507	$14,330
500	$7,567	$9,388	$11,210	$13,032	$14,853
1000	$7,624	$9,446	$11,267	$13,089	$14,910

Table 4. Cost comparison (5-ft centers), non-ideal site

Non-Ideal Site Savings per Acre – Level D Typical Fully Burdened Labor Rates Acres	$40	$50	$60	$70	$80
2	($6,297)	($6,023)	($5,750)	($5,477)	($5,203)
5	($3,749)	($3,523)	($3,298)	($3,073)	($2,847)
10	($2,461)	($2,251)	($2,042)	($1,833)	($1,623)
50	($871)	($674)	($478)	($281)	($85)
100	($501)	($306)	($112)	$83	$278
500	($205)	($12)	$182	$375	$569
1000	($146)	($47)	$241	$434	$628
Savings per Acre – Level C					
Acres					
2	($8,369)	($7,902)	($7,435)	($6,969)	($6,502)
5	($5,242)	($4,823)	($4,404)	($3,986)	($3,567)
10	($4,423)	($4,020)	($3,617)	($3,215)	($2,812)
50	($362)	$28	$418	$808	$1,198
100	$138	$526	$914	$1,303	$1,691
500	$574	$961	$1,348	$1,735	$2,122
1000	$650	$1,037	$1,424	$1,811	$2,197

Table 5. Cost comparison (2-ft centers), non-ideal site

Non-Ideal Site Savings per Acre – Level D Typical Fully Burdened Labor Rates Acres	$40	$50	$60	$70	$80
2	($3,091)	($2,100)	($1,109)	($119)	$872
5	($543)	$400	$1,343	$2,285	$3,228
10	$745	$1,672	$2,599	$3,525	$4,452
50	$2,335	$3,249	$4,163	$5,077	$5,990
100	$2,075	$3,617	$4,529	$5,441	$6,354
500	$3,001	$3,911	$4,822	$5,733	$6,644
1000	$3,060	$3,971	$4,882	$5,792	6,703
Savings per Acre – Level C					
Acres					
2	($1,957)	($55)	$1,846	$3,747	$5,649
5	$1,170	$3,024	$4,877	$6,730	$8,584
10	$1,989	$3,827	$5,664	$7,501	$9,339
50	$6,050	$7,875	$9,699	$11,524	$13,348
100	$6,550	$8,373	$10,196	$12,019	$13,842
500	$6,986	$8,807	$10,629	$12,451	$14,272
1000	$7,062	$8,884	$10,705	$12,527	$14,348

Cost Conclusions

- Magnetometer Towed Array is cost effective for surveys greater than 50 acres.
- Magnetometer Towed Array is cost effective for surveys requiring 2-ft centers on sites greater than 2 to 5 acres.
- Grid-spacing requirements are directly related to the amount of data required to characterize a given site adequately.
  - If the site contains only trenches and the goal is to identify those trenches, 5-ft spacing is adequate. Magnetometer Towed Array would not be cost effective until the site becomes very large.
  - If the site contains an ill-defined burial location or the extent of the anomalous objects needs to be precisely defined, 2-ft grid spacings may be of benefit. Magnetometer Towed Array may be suited to this type of site.

SECTION 6

REGULATORY AND POLICY ISSUES

Regulatory Considerations

- No special issues are involved with using the Magnetometer Towed Array versus traditional technology. The same issues that apply to the traditional technology apply to the Magnetometer Towed Array because the Magnetometer Towed Array is an improved method to deploy magnetometry technology and to analyze magnetometric data. Regulatory approval is not typically required to perform characterization screening. However, it is l ikely that regulators will require some confirmatory drilling to validate the survey data.
- A site safety and health plan will be required and will have to address the same issues that are addressed in the traditional technology.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

The Magnetometer Towed Array may be more protective of the worker when compared with traditional technology

- The worker can survey the site much faster, thus reducing exposure to the site hazards.
- Only one person is exposed at the site, whereas traditional approaches are usually performed by two people for grid layout and another person to conduct the survey.

Community Safety

No adverse reaction is expected by use of the Magnetometer Towed Array.

Risks/Benefits

- The Magnetometer Towed Array has the same risks and benefits as the traditional technology.
- Some probability exists that the magnetometer survey will fail to provide the data needed to characterize the site. The technology is capable of sensing only buried feromagnetic objects near the surface. Lack of detectable materials may result in a failure to define a burial area. Naturally occurring materials may result in a false positive conclusion. For these reasons, follow-up confirmational investigations such as test pits and soil borings are usually performed.
- Because of the high-density sampling, the Magnetometer Towed Array improves the screening assessment accuracy.

SECTION 7

LESSONS LEARNED

Implementation Considerations

- The first consideration must be whether a non-intrusive survey technology is going to aid the investigation process. If one concludes that a non-instrusive survey is needed, then one must determine that passive techniques such as magnetometry will work or whether active techniques such as ground-penetrating radar are more appropriate.
- If one determines that magnetometry techniques will be suitable for site characterization, a cost-effectiveness evaluation will aid the selection of the Magnetometer Towed Array.

Technology Limitations and Needs for Future Development

- The development activities were successful in that the demonstrations in 1993 and 1994 showed that the initial deficiencies with the vehicle durability and locator system had been corrected.
- When the technology is used at hazardous waste sites, most customers are using the Magnetometer Towed Array for characterizing the extent of burial trenches, not for determination of object size and depth. Size and depth determination remains an area where further development is necessary before reliable interpretation can be produced.
- During the demonstration at MDA C, investigators found that the cesium vapor detectors had a dead zone where the earth field lines were oriented such that the detectors were unable to sense the strength of the field. They concluded that pitch-and-roll inclinometers may be necessary and that different sensors may need to be considered for future development.
- NRL continues to work on development of this technology. Their primary interest is characterization of buried ordnance sites where false positive identification and size and depth are important data needs. Characterization of buried waste sites will only improve by these efforts. Note that NRL is not working to address deficiencies observed with software handling of multiple objects, multiple depths, and object orientation learned during the development program conducted by the DOE/NRL team.

APPENDIX A

REFERENCES

Bremser, J. P., and S. R. Booth. ND *Cost Effectiveness of the Surface Towed Ordnance Locator System (STOLS),* LA-UR-93-4396, Los Alamos National Laboratory, Los Alamos, N. M., (SECTION 1, 4, 5, 6, and 7)

Cochran, J. R., J. R. McDonald, and R. J. Russell. 1995. *Adaptation of the Magnetometer Towed Array Geophysical System to Meet Department of Energy Needs for Hazardous Waste Site Characterization,* SAND95-2087, Sandia National Laboratory, Albuquerque, N. M., (SECTION 1, 2, 3, 4, 6, and 7)

Foley, J. E. 1994. "Environmental Characterization with Magnetics and STOLS™," reprint from *Proceedings of the IEEE,* December 1994, (SECTION 2)

Foley, J. E. ND. *STOLS™ Magnetic Survey at Sandia National Laboratory Technical Area 2,* Geo-Centers, Inc., Newton Center, Mass., (SECTION 2, 3, 6, and 7)

McDonald, J. R., R. Robertson, and J. R. Cochran. 1994. TA-73, *The Airport Landfill, A Magnetometer Towed-Array Survey,* NRL/PU/6110-95-227, Los Alamos National Laboratory, Naval Research Laboratory, Los Alamos, N. M., (SECTIOM 3, 6, and 7)

McDonald, J. R., and R. Robertson. 1995. *Results of a Magnetometry Survey at TA-50, MDA C,* NRL/PU/6110-95-2978, Los Alamos National Laboratory, Naval Research Laboratory, Los Alamos, N. M., (SECTION 3, 6, and 7