Final Report on 2002 Airborne Geophysical Survey at Pueblo of Laguna Bombing Targets, New Mexico

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14. ABSTRACT
This report describes the results of a low altitude helicopter geophysical survey performed by US Army Engineering Support Center, Huntsville (USAESCH) and Oak Ridge National Laboratory (ORNL) over areas contaminated by unexploded ordnance on Pueblo of Laguna Nation lands in April/May, 2002. The purpose of the survey was to evaluate improvements to a multi-sensor magnetometry system for ordnance detection. Surveys were carried out at four areas where the Department of Defense previously had conducted bombing exercises. These areas totaled over 1640 hectares. In addition, a 0.03 hectare calibration grid was surveyed. In two of the areas, 90 m x 350 m grids were measured with the MTADS ground magnetometer system, and anomalies were excavated. No live ordnance was found. Of a total of 576 excavated items classed as UXO fragments in areas N-09 and N-10, 432 were within a 2 m radius of aerial anomaly locations, yielding an overall find ratio (number of helicopter detections/total MTADS detections) of 75%. However, many of these undetected items may have been too small for detection by helicopter systems.

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Acronym List

AGL	Above ground level
AS	Analytic signal
ASCII	American Standard Code for Information Interchange
ADU	Attitude determination unit
BBR	Badlands Bombing Range, South Dakota
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
DAS	Data analysis system
DoD	Department of Defense
DQO	Data Quality Objective
ESTCP	Environmental Security Technology Certification Program
FAA	Federal Aviation Administration
GIS	Geographic Information System
GPS, DGPS	(Differential) Global Positioning System
HAZWOPR	Hazardous Waste Operations and Emergency Response
INS	U.S. Immigration and Naturalization Service
MTADS	Multi-Sensor Towed Array Detection System
NAD	North American Datum
ORAGS	Oak Ridge Airborne Geophysical System
ORNL	Oak Ridge National Laboratory
SERDP	Strategic Environmental Research & Development Program
TIF, GeoTIF	(Geographically referenced) Tagged Information File
TF	Total (magnetic) field
USAESCH	U.S. Army Engineering and Support Center, Huntsville
UTM	Universal Transverse Mercator
UXO	Unexploded Ordnance

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Abstract

This report describes the results of a low altitude helicopter geophysical survey performed by U.S. Army Engineering Support Center, Huntsville (USAESCH) and Oak Ridge National Laboratory (ORNL) over areas contaminated by unexploded ordnance on Pueblo of Laguna Nation lands in April/May, 2002. The purpose of the survey was to evaluate improvements to a multi-sensor magnetometry system for ordnance detection. Surveys were carried out at four sizeable areas on the Pueblo where the Department of Defense previously had conducted weapons tests and bombing exercises. These areas totaled over 1640 hectares. In addition, a 0.03 hectare calibration grid was surveyed. In two of the areas, 90 m x 350 m grids were measured with the MTADS ground magnetometer system, and anomalies were excavated. No live ordnance was found. Of a total of 576 excavated items classed as UXO fragments in areas N-09 and N-10, 432 were within a 2 m radius of aerial anomaly locations, yielding an overall find ratio (number of helicopter detections/total MTADS detections) of 75%. However, many of these undetected items may have been too small for detection by helicopter systems. The average distance between the actual locations of the excavated items and the predicted locations from helicopter anomalies was 100 cm.

1.0 Introduction

1.1 Background

Portions of lands belonging to the Pueblo of Laguna Nation have been contaminated with unexploded ordnance (UXO) through Department of Defense (DoD) activities, e.g. during training exercises or during weapons tests. As there was no clear understanding as to the nature and extent of the UXO contamination, a low-altitude airborne geophysical survey was conducted in order to demonstrate its efficacy as an economical rapid reconnaissance tool at UXO sites.

This report describes the results of a low altitude helicopter geophysical survey performed by Oak Ridge National Laboratory (ORNL) and the U.S. Army Engineering Support Center, Huntsville (USAESCH) over UXO-contaminated areas on Pueblo of Laguna Nation lands. The areas, located west of Albuquerque, New Mexico, were flown in four survey blocks designated N-09, N-10, N-11 and S-12. Supplemental data were also acquired over a temporary calibration site. Surveys were flown so as to completely cover the central section of the bombing targets. Additional lines were flown at a wider spacing beyond the target center to characterize the outer extent of the contamination without the need to fully cover the entire area.

The survey was carried out from April 10 to May 6, 2002. Mobilization of U.S. and Canadian-based crews began on April 10; however, U.S. Immigration and Naturalization Services (INS) grounded the aircraft and air crew at the U.S.-Canada border until April 19 because of insufficient equipment documentation. During this period between the start of mobilization and the arrival of the air crew, each of the survey grids was investigated on the ground, and the Calibration Site was prepared and surveyed using ground-based geophysical instruments. Upon arrival of the Canadian aircraft and crew, equipment installation and calibration flights were conducted. Total magnetic field data were collected between April 21 and April 29. Between April 30 and May 4, surveys using an experimental electromagnetic survey system and a vertical magnetic gradient system were conducted over portions of several target areas for the Environmental Security Technology Certification Program (ESTCP) and the Strategic Environmental Research and Development Program (SERDP) in cooperation with the Pueblo of Laguna Nation. This report addresses only the total magnetic field system and data. Treatment and discussion of the vertical magnetic gradient system and the electromagnetic system are covered in separate reports.

1.2 Objectives of the Demonstration

The objectives of the demonstration survey are:

- To provide a means of determining the improvement resulting from recent modification in the Oak Ridge Airborne Geophysical System (ORAGS) total field magnetometry system;
- To assess the capabilities of the system at a site representing conditions and ordnance types typically found on former DoD ranges;
- To detect and map UXO and UXO-related items for subsequent clearance actions.

The survey was accomplished using the ORAGS Arrowhead magnetometer array, shown in Figures 2.1 and 2.2.

1.3 Regulatory Drivers

UXO clearance is generally conducted under CERCLA authority. Irrespective of lack of specific regulatory drivers, many DoD sites and installations are pursuing innovative technologies to address a variety of issues associated with ordnance and ordnance-related artifacts (e.g. buried waste sites or ordnance caches) that resulted from weapons testing and/or training activities. These issues include footprint reduction and site characterization, areas of particular focus for the application of technologies in advance of future regulatory drivers and mandates.

1.4 Stakeholder/End-User Issues

The Laguna sites are formerly used defense sites and as such it is important that concentrations of ordnance and locations of possibly live ordnance be mapped so that actions can be taken toward removal of UXO or safeguards can be established where there is the possibility that live ordnance is still in place. It is also important that a permanent record be maintained to document all measurements that are made to support clearance activities. Advanced technology is expected to contribute to the performance of these activities in terms of efficiency as well as cost.

2.0 Technology Description

2.1 Technology Development and Application

The total field system is a fourth-generation airborne magnetometer array (Figures 2.1 and 2.2) that we have designated as the ORAGS-Arrowhead system. Changes from the previous ORNL airborne magnetometer array, the ORAGS-Hammerhead, include a new boom architecture designed to position sensors at low-noise locations, and a new aircraft orientation system. The new attitude determination system is based on four Global Positioning System (GPS) antennas rather than fluxgate magnetometer measurement as in previous generations. For the ORAGS-Arrowhead system, four magnetometers at 1.7-meter spacing are located in a forward V-shaped boom, and two magnetometers with equivalent spacing are located in each of the lateral booms. Although the spacing is similar to that of the predecessor ORAGS-Hammerhead system, the forward positioning of two magnetometers that were previously the innermost rear boom magnetometers on the Hammerhead system improves noise conditions over those of the Hammerhead system.

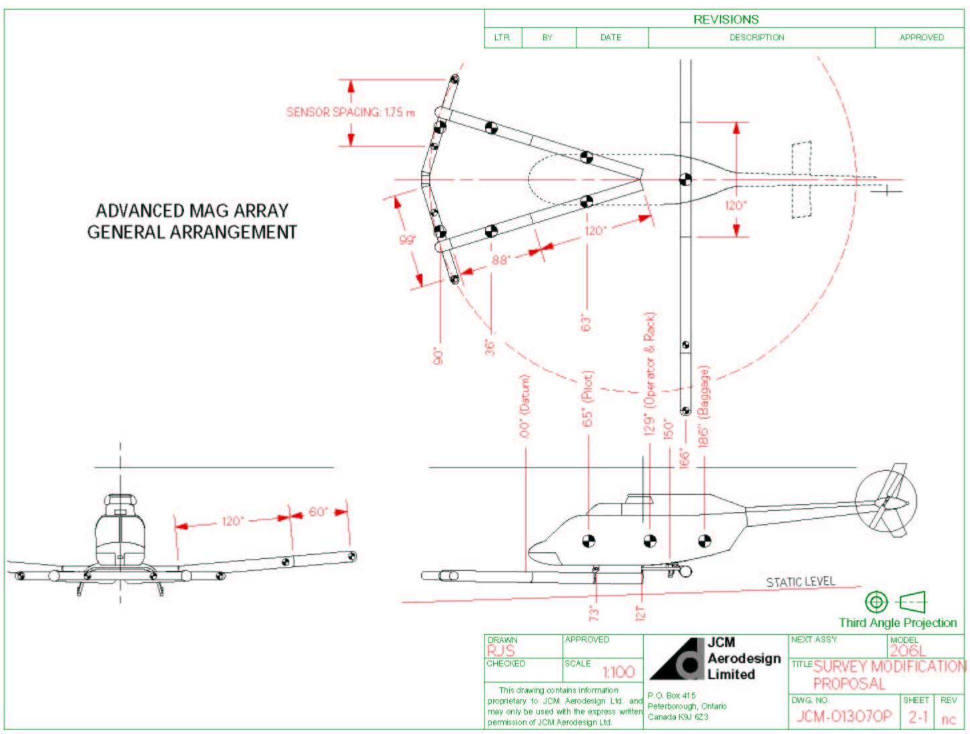

Figure 2.1 Schematic for the ORAGS-Arrowhead airborne total field magnetometer system that has been constructed to evaluate the improvements over previous generations of total field systems.

Figure 2.2 ORAGS-Arrowhead helicopter total field magnetometry system.

2.2 Previous Testing of the Technology

ORNL has previously tested two generations of boom-mounted airborne magnetometer systems for UXO detection and mapping. The first system tested was the HM-3 system, depicted in Figure 2.3, developed by Aerodat, Ltd., under the direction of J.S. Holladay and T. J. Gamey. The 1999 airborne magnetometer tests at BBR deployed this system, operated by High Sense Geophysics, and was modified to meet ORNL requirements (Gamey et al., 2000).

In September 2000, ORNL deployed a more advanced helicopter system at BBR, the ORAGS-Hammerhead system, in cooperation with Dr. Holladay (now at Geosensors Inc., a teaming partner with ORNL) and Mr. Gamey (now at ORNL). While somewhat similar in appearance to the HM-3 system, this system, illustrated in Figure 2.4, is significantly improved in terms of the number of magnetometers, magnetometer spacing, system positioning, navigation, and data acquisition parameters (Doll et al., 2001; Gamey et al., 2001). Additionally, a dihedral in the boom tubes improved system safety by raising the boom tips.

Figure 2.3 The HM-3 helicopter magnetometry system used by ORNL in 1999 for surveys at Badlands Bombing Range.

Figure 2.4 ORAGS-Hammerhead airborne magnetometer system used at Badlands Bombing Range in FY2000.

2.3 Factors Affecting Cost and Performance

The cost of an airborne survey depends on several factors, including:

- Helicopter service costs, which depend on the cost of ferrying the aircraft to the site and fuel costs, among other factors.
- The total size of the blocks to be surveyed
- The length of flight lines
- The extent of topographic irregularities or vegetation that can influence flight variations and performance
- Ordnance objectives which dictate survey altitude and number of flight lines
- The temperature and season, which control the number of hours that can be flown each day
- The location of the site, which can influence the cost of logistics
- The number of sensors and their spacing; systems with too few sensors may require more flying, particularly if they require interleaving of flight lines
- Survey objectives and density of coverage, specifically high density for individual ordnance detection versus transects for target/impact area delineation and footprint reduction

2.4 Advantages and Limitations of the Technology

Airborne surveys for UXO are capable of providing data for characterizing potential UXO contamination at a site at considerably lower cost than ground-based systems. Current indications are that the survey cost may approach $70.00 per acre under *optimal* conditions. Furthermore, the data may be acquired and processed in a shorter period of time, thereby reducing the time required for reviewing large areas. Airborne systems are particularly effective at sites having low-growth vegetation and minimal topographic relief. They can also be used where heavy brush or mud makes it difficult to conduct ground-based surveys.

Both airborne and ground magnetometer systems are susceptible to interference from magnetic rocks and magnetic soils. Rugged topography or tall vegetation limits the utility of helicopter systems, necessitating survey heights too high to resolve individual UXO items.

3.0 Demonstration Design

3.1 Performance Objectives

Shown in Table 3.1 is a listing of the various performance objectives for this survey.

Table 3.1 – Performance Objectives of Arrowhead Airborne Magnetic System

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Qualitative	Total Field (TF) system aerodynamically stable	Pilot report	Yes
Quantitative	TF system has lower noise than predecessors	Comparison of data sets at test site and elsewhere	Yes
Qualitative/Quantitative	New attitude measurement system provides improved sensor positioning	Comparison of ground follow-up results for target reacquisition radius and comparison of processed results over small known targets	Yes, however difficulties with ADU caused much data to have only marginally improved accuracy.
Qualitative/Quantitative	Improved aircraft compensation over previous systems	Comparison of Figure of Merit (FOM) and compensated profiles with those from Hammerhead system data	No
Quantitative	Probability of detection	>90%	No
Quantitative	False alarm rate	6%	No
Quantitative	Location accuracy	<100 cm	No
Quantitative	Survey rate	>40 acres/hr	Yes
Quantitative	Percent site coverage	100%	Yes

3.2 Selecting Test Sites

The airborne survey sites were chosen to enable, where possible, direct comparison of results from the new generation airborne systems with results of ground-based geophysical systems for UXO detection and mapping. Airborne data were acquired at five sites at Pueblo of Laguna. Two of these sites had been previously surveyed by the NRL MTADS magnetometer array (McDonald and Nelson, 1999) under the guidance of the ESTCP Program Office. The five survey sites for this demonstration project are: (1) a small Calibration Site established at Pueblo of Laguna using inert ordnance items and ordnance simulants, and (2)-(5), four bombing targets on Pueblo of Laguna, identified as Kirtland PBR N-9, Kirtland PBR N-10, Kirtland PBR N-11, and Kirtland PBR S-12. All sites were remote, but accessible by both road and air, and were found to contain significant M38 ordnance debris at the surface. MTADS surveys of the N-9 and N-10 sites were conducted in 1998 and indicated the presence of significant numbers of M38 practice ordnance. In addition to the surface surveys, the MTADS team performed several hundred intrusive investigations and excavations.

3.3 Test Site History/Characteristics

The sites selected within the Pueblos of Laguna are formerly used defense sites (FUD Sites) located west of Albuquerque in New Mexico. Totaling more than half a million acres, large portions of this typically western desert environment are flat and devoted to ranching. The remaining portions of land are gently rolling to nearly vertical in appearance that have been formed due to the extensive erosion of the soft fine-grained underlying sediments, creating canyons, washes, and gullies.

The Pueblo is situated on the eastern edge of the New Mexico portion of the Colorado Plateau, east of the Albuquerque-Belen Basin. Separating the geologic provinces is a series of strong north-south trending high-angle faults stepping downward from the plateau into the basin. The geology of the area is dominated by both consolidated and unconsolidated units and includes sandstone, mudstone, claystone, and shale. Igneous basalt formations cap the mesas in the area. Typical altitude at the sites is 5,000-6,000 feet above sea level.

With regard to historical ordnance, numerous sites exist across the entire area that were utilized for aerial bombardment activity, including the four areas identified for this demonstration. From both visual inspection and previous NRL MTADS surveys, the principal ordnance type present at these sites is the M38 practice bombs. Evidence of these ordnance items is present on the surface at all sites under consideration for this demonstration, with several hundred M38s excavated during the MTADS demonstration (McDonald and Nelson, 1999).

3.4 Present Operations

Two of the sites at Pueblo of Laguna had been previously surveyed by the NRL MTADS magnetometer array (McDonald and Nelson, 1999) under the guidance of the ESTCP Program Office. No remediation work had been done at the site prior to the MTADS survey.

3.5 Pre-Demonstration Testing and Analysis

Shakedown testing of the assembled airborne system and associated components was conducted in Toronto, Ontario, Canada during December 10-21, 2001. These tests were used to determine whether the completed system, and its components, were performing as designed.

The airborne magnetic system was flight tested by an aeronautical engineer and determined to be completely flightworthy. The testing validated both the aerodynamic stability and performance of the system. Magnetic noise levels for the system were measured both on the ground and during flight. Total magnetic field data were collected at low altitude over known targets in a seeded test area.

One of the main design changes made in moving from the ORAGS-Hammerhead design to the ORAGS-Arrowhead design was to shift the positions of sensors 3 and 6—the innermost magnetometers on the aft booms of the Hammerhead system, located 2.6 m from the helicopter centerline. On the Arrowhead system, sensors 3 and 6 were re-positioned to the outer parts of the foreboom. This effectively cut in half the noise levels of sensors 3 and 6 without compromising the efficiency of the aerodynamics or the quality of the data from the other sensors.

In summary, all system components in both airborne systems performed as anticipated. The noise levels at the aft inboard magnetometer positions 4.3 meters from the centerline of the helicopter is somewhat higher than the noise levels of the other magnetometers, but is reduced over inboard magnetometers from the ORAGS-Hammerhead system, which were located only 2.6 m from the helicopter centerline. Flight performance and maneuverability were excellent with no ballast required.

3.6 Testing and Evaluation Plan

3.6.1 Demonstration Set-Up and Start-Up

Mobilization involved packing and transporting all system components by trailer to Albuquerque and installing them on a Bell 206L Long Ranger helicopter. Calibration and compensation flights were conducted and results evaluated. The eight cesium magnetometers, GPS systems (positioning and attitude), fluxgate magnetometers, data recording console, and laser altimeter were tested to ensure proper operation and performance. The Mission Plan was read and signed by all project participants to assure safe operation of all systems.

3.6.2 Period of Operation

Mobilization of the geophysical crew from Oak Ridge, Tennessee and the flight crew from Toronto, Canada began on April 10, 2002. This required two days travel to Albuquerque for the geophysical equipment trailer. A delay at the Canada-U.S. border postponed the air crew's arrival until April 18. Installation began on the afternoon of April 18. Calibration site set-up, as well as pre-seed and post-seed ground-based surveys, and site visits took place during the mobilization period. Airborne systems demonstration and testing, including test of two other ORNL airborne systems, continued through May 04. De-installation began in the afternoon of May 04, and the geophysical and air crews departed for Oak Ridge and Toronto, respectively.

3.6.3 Area Characterized

A total of six sites were surveyed. Of the six, four were large area surveys encompassing bombing or artillery targets. The areas surveyed at these sites are: S-12, 341 ha; N-9, 455 ha; N-10, 448 ha; and N-11, 403 ha. The site of the calibration grid had an area of only 0.03 ha. The total area surveyed by the total field system is thus 1647 ha. At the four large sites, only the central portion of the sites, amounting to about 20 percent of the total area at each site, was surveyed at 100 percent coverage using a 12-m flight line spacing. Outside the central band, the line spacing was a factor of four times less dense.

3.6.4 Residuals Handling

This section does not apply to this report.

3.6.5 Operating Parameters for the Technology

The ORAGS Arrowhead system is designed for daylight operations only. Lines were flown in a generally east-west or north-south pattern depending on local logistics and weather conditions with a nominal 12m flight line spacing for the high density survey coverage and 48m flight line spacing for the statistical sampling coverage. Binary data from the eight magnetometers was recorded on the console at a rate of 1200 samples per second. A typical survey speed for the system was 100 km/hr. Survey height was 1-3 m above ground level. In areas where background magnetic susceptibility and variation is small, vegetation height low, and topographic change gradual, the system can be expected to detect anomalies as small as 2 nT, and ferrous masses as small as 2 kg UXO fragments. These thresholds can be expected to increase as any of the aforementioned variables increase.

3.6.6 Experimental Design

The tests conducted with the ORAGS-Arrowhead total magnetic field system are summarized in Table 3.2.

Table 3.2 - Field Tests with Arrowhead Total magnetic field System

Test ID	Description	Parameters	Sites
Standard configuration	Test overall system performance (aerodynamics, noise, compensation, positioning, orientation, detection)	Alt = 2m at Calibration Site Alt = 2m at four Pueblo of Laguna sites	Full survey coverage of the Calibration Site, and partial coverage of four Pueblo of Laguna sites.

Data quality objectives (DQOs) to be used for this technology demonstration focused on prior-generation airborne results as the baseline performance condition, as well as previous MTADS demonstration data. Analysis of HM-3 data by the Institute for Defense Analyses (Andrews et al., 2001) of the same ORNL data sets yielded 78% to 83% ordnance, 17% to 24% false positives. A subsequent analysis by Scott Holladay of Geosensors confirmed these figures. Holladay's calculations yielded 83% ordnance, 17% false positives, and 0% false negatives (ORNL, 2002). Subsequent ORAGS-Hammerhead airborne surveys at BBR, Shumaker Naval Ammunition Depot and Rocket Test Range, Nomans Land Island, and New Boston Air Force Station yielded results consistent with the previous surveys at BBR. One difference is that positional accuracy of the data has improved from approximately 2m in Hammerhead tests to about 1m with the Arrowhead system. This we attribute to the fact that by moving sensors 3 and 6 to the forward boom, they were closer to the GPS sensor than in the Hammerhead assembly, and less susceptible to mispositioning caused by helicopter yaw.

Given the various considerations associated with both the interpretation of airborne geophysical survey data and the calculations of the various performance parameters, DQOs for the demonstration of the fourth-generation total field system approached or met the current performance parameters. ORNL expected the ORAGS-Arrowhead total field system to provide detection in the vicinity of 90% ordnance with 5% to 7% false positives. The methodology used to acquire the airborne data is as described in previous sections of this document with a variety of altitudes flown. All surveys conducted with the Arrowhead total field system were performed as high-density surveys with line spacing established to account for sensor positions such that no gaps or voids exist in any data set, except where planned. Positioning for the anomalies detected, being about 100 cm, fell somewhat short of the performance metric of 60 cm.

Data processing procedures

The 1200 Hz raw data were desampled in the signal processing stage to a 60 Hz recording rate. All other raw data were recorded at a 60 Hz sample rate. Data were converted to an ASCII format and imported into a Geosoft format database for processing. With the exception of the differential GPS post-processing, all data processing was conducted using the Geosoft software suite and proprietary ORNL algorithms and filters. The quality control, positioning, and magnetic data processing procedures (steps a-i) are described below.

Quality Control

All data were examined in the field to ensure sufficient data quality for final processing. The adequacy of the compensation data, heading corrections, time lags, orientation calibration, overall performance and noise levels, and data format compatibility were all confirmed during data processing. During survey operations, flight lines were plotted to verify full coverage of the area. Missing lines or areas where data were not captured were reacquired. Data were also examined for high noise levels, data drop outs, significant diurnal activity, or other unacceptable conditions. Lines flown, but deemed to be unacceptable for quality reasons, were re-flown.

Positioning
During flight, the pilot was guided by an on-board navigation system that used real-time satellite-based DGPS positions. This provided sufficient accuracy for data collection (approximately 1m), but was inadequate for final data positioning. To increase the accuracy of the final data positioning, a base station GPS was established at Albuquerque International Airport at location (NAD83 35° 02' 11.51050" N 106° 37' 17.19129" W NAVD88 1605.50m). Raw data in the aircraft and on the ground were collected. Differential corrections were post-processed to provide increased accuracy in the final data positioning. The final latitude and longitude data were projected onto an orthogonal grid using the North American Datum 1983 (NAD 83) UTM Zone 13N. Vertical positioning was monitored by laser altimeter with an accuracy of 2cm. No filtering was required of these data, although occasional drop-outs were removed.

Magnetic data processing procedure
The magnetic data were subjected to several stages of geophysical processing. These stages included correction for time lags, removal of sensor dropouts, compensation for dynamic helicopter effects, removal of diurnal variation, correction for sensor heading error, array balancing, and removal of helicopter rotor noise. The calculation of the magnetic analytic signal was derived from the corrected residual magnetic total field data.

(a) Time Lag Correction
There is a lag between the time the sensor makes a measurement and the time it is time stamped and recorded. This applies to both the magnetometer and the GPS. Accurate positioning requires a correction for this lag. Time lags between the magnetometers, fluxgate magnetometer, and GPS signals were measured by a proprietary ORAGS firmware utility. This utility sends a single pulse that is visible in the data streams of all three instruments. This lag was corrected in all data streams before processing.

(b) Sensor Dropouts
Cesium vapor magnetometers have a preferred orientation to the Earth's magnetic field. As a result of the motion of the aircraft, the sensor dead zones can occasionally align with the Earth's field. In this event, the readings drop out, usually from an average of 53,000 nT to 0 nT. This usually only occurs during turn-around between lines, and rarely during actual data acquisition. All dropouts were removed manually before processing.

(c) Aircraft Compensation
The presence of the helicopter in close proximity to the magnetic sensors results in considerable deviation in the readings, and generally requires some form of compensation. The orientation of the aircraft with respect to the sensors and the motion of the aircraft through the earth's magnetic field are also contributing factors. A special calibration flight is performed to record the information necessary to remove these effects. The maneuver consisted of a square or rectangular-shaped flight path at high altitude to gain information in each of the cardinal directions. During this procedure, the pitch, roll and yaw of the aircraft were varied. This provided a complete picture of the effects of the aircraft at all headings in all orientations. The

entire maneuver was conducted twice for comparison. The information was used to calculate coefficients for a 19-term polynomial for each sensor. The fluxgate data were used as the baseline reference channel for orientation. The polynomial is applied post flight to the raw data, and the results are generally referred to as the compensated data. This data is used in the development of the analytic signal maps presented in this report.

(d) Magnetic Diurnal Variations
The earth's magnetic field changes constantly over the course of the day. This means that magnetic measurements include a randomly drifting background level. A base station sensor was established near the GPS base station monument at Albuquerque International Sunport to monitor and record this variation every five seconds. The recorded data are normally subtracted directly from the airborne data. The time stamps on the airborne and ground units were synchronized to GPS time. The diurnal activity recorded at the base station was extremely quiet. In general, the low frequency diurnal variations were less than 5nT per survey line. Processing included defaulting repeated values and linearly interpolating between the remaining points.

(e) Heading Corrections
Cesium vapor magnetometers are susceptible to heading errors. The result is that one sensor will give different readings when rotated about a stationary point. This error is usually less than 0.2 nT. Heading corrections were applied to adjust readings for this effect.

(f) Array Balancing
These magnetic sensors also provide a lower degree of absolute accuracy than relative accuracy. Different sensors in identical situations will measure the same relative change of 1 nT, but they may differ in their actual measured value, such as whether the change was from 50,000 to 50,001 nT or from 50,100 to 50,101 nT. After individual sensors were heading-corrected to a uniform background reading, the background level of each sensor was corrected or balanced to match the others across the entire airborne array.

(g) Regional Removal
Deep-seated, large scale background geology and some cultural features which contribute to the local regional magnetic field were removed using a combination of filtering and splining techniques. The output is a residual magnetic total field. This process also removed all diurnal, heading and balancing effects.

(h) Rotor Noise
The aircraft rotor spins at a constant rate of approximately 400 rpm. This introduces noise to the magnetic readings at a frequency of approximately 6.6 Hz. Harmonics at multiples of this base are also observable, but are much smaller. This frequency is usually higher than the spatial frequency created by near surface metallic objects. This effect has been removed with a low-pass frequency filter.

(i) Analytic Signal

The data resulting from this survey are presented in the form of analytic signal. The square root of the sum of the squares of the three orthogonal magnetic gradients is the total gradient or analytic signal. It represents the maximum rate of change of the magnetic field in any direction (i.e. a measure of how much the readings would change by moving a small amount in any direction such as left-right, forward-backward, or up-down). This parameter was calculated from the gridded residual total field data.

There are some advantages to using the analytic signal. For small objects, it is somewhat more straightforward to interpret visually than total field data. Total field measurements typically display a dipolar response signature to small, compact sources, having both a positive and negative deviation from the background. The actual source location is a point between the two peaks, as determined by the magnetic latitude of the site and the properties of the source itself. Analytic signal is more symmetric about the target, is always a positive value and has less dependence on magnetic latitude. Analytic signal maps present anomalies as low intensity to high intensity shapes.

3.6.7 Sampling Plan

This section does not apply to this report.

3.6.8 Demobilization

De-installation was carried out on May 04. Booms were dismounted from the helicopter frame and the magnetometers and GPS instrumentation were disconnected and packed in shipping containers. The containers were placed in a trailer for transport to ORNL. The helicopter crew demobilized and departed for Ontario on May 05, 2002.

4.0 Performance Assessment

4.1 Performance Criteria

Demonstration effectiveness is determined directly from comparisons of the processed/analyzed results from the demonstration surveys and the results of previous airborne and ground-based surveys. These comparisons include both the quantitative and qualitative items described in this section. Demonstration success is determined as the successful acquisition of airborne geophysical data (without any aviation incident or airborne system failure) and meeting the baseline requirements for system performance as established previously in this document (Section 3.1). Methods utilized by ORNL on both current and past airborne acquisitions to ensure airborne survey success include daily QA/QC checks on all system parameters (e.g. GPS, magnetometer operation, data recording, system compensation measurements, etc.) in the acquired data sets, a series of compensation flights at the beginning of each survey, continual inspection of all system hardware and software ensuring optimal performance during the data acquisition phase, and review of data upon completion of each processing phase.

Several factors associated with data acquisition cannot be strictly controlled, such as aircraft altitude and attitude. Altitude can be recorded and will enter into the data analysis and comparisons with previous results. The aircraft attitude measuring system provides a documented database that cannot be directly compared with previous surveys when this system was not available. The consistent and scientific evaluation of performance is accomplished by using identical or parallel (where parameters are dataset dependent) processing methods with identical software to produce a final map, and following consistent procedures in interpretation when comparing new and existing datasets from the test sites.

Data processing involves several steps, including GPS post-processing, compensation, spike removal, removal of magnetic diurnal variations, time lag correction, heading correction, filtering, gradient calculations, and gridding. Each step is performed in the same manner on data acquired with sequential generations of system at the same sites, to provide a basis for comparing the performance of the systems. The processing procedures have been selected and developed from experience with similar data over a span of more than five years for optimal sensitivity to UXO.

Data quality objectives, as described in Section 3.6.6 (Experimental Design), were used for this demonstration. Surveys over the previously described test areas were conducted as described in Section 3.6. Data collection occurred at flight altitudes over the various test areas and configurations as described in Section 3.6.6. Data confirmation was in accordance with the processes previously described in this section.

Table 4.1 identifies the expected performance criteria for this demonstration, complete with expected/desired values (quantitative) and/or definitions and descriptions (qualitative). This table also identifies expected performance for each of the technologies present in this demonstration.

Table 4.1: Performance Criteria

Performance Criteria	Expected Performance Metric (Pre-demo)	Performance Confirmation Method	Actual Performance (Post-demo)
Primary Criteria (Performance Objectives) – Quantitative			
System Performance (total field system)	Ordnance detection* – greater than 90%	Comparison to prior collected airborne and ground-based data	87%
System Performance (total field system)	False positives – less than or equal to 6%	Comparison to prior collected airborne and ground-based data	13%
System Performance (total field system)	Data acquisition rate – greater than or equal to 40 acres per hour	Comparison to prior ORNL-conducted airborne surveys	> 140 acres/hour, including turnaround time
System Performance (total field system)	Detection threshold (sensitivity)	Comparison to prior collected ground-based geophysical data	~5-7 nT for reliable detection
System Performance (total field system)	Anomaly positional accuracy	Comparison to known benchmarks and known (documented) anomalies at the test site locations	~1.0m
Primary Criteria (Performance Objectives) – Qualitative			
Process Waste	None	Observations	No process waste.
Factors Affecting Technology	Helicopter geophysical noise	Comparison to expected noise levels based on prior geophysical measurements around the helicopter	Noise lower than in previous surveys.
Factors Affecting Technology	Helicopter geophysical noise	Comparison of sensor compensation measurements against prior compensation values	Lower noise for sensors 3 and 6.
Factors Affecting Technology	Helicopter movement	Record constellation changes and use during positioning accuracy	Recorded.

		determination	
Secondary Criteria (Performance Objectives) – Quantitative			
Hazardous Materials	None expected, other than spotting charges in M38 practice ordnance	Observations and documentation during excavations	All UXO-related materials excavated were labeled UXO-fragments
Secondary Criteria (Performance Objectives) – Qualitative			
Reliability	No system or component failures	Observations and documentation	No components failed during the total field surveys
Ease of Use	Pilot "comfort" when flying with the system installed	Observations and documentation	Pilot states that he feels at ease flying the system under normal wind conditions
Ease of Use	No ballast required	Observations and documentation	Engineer declared the system balanced without need for ballast
Safety	Conformance with all FAA requirements and requirements as documented in the Mission Plan	Observations and documentation	System met all FAA flightworthiness requirements
Versatility	Cultural feature detection and mapping	Comparison of anomaly count, strength, and position to previously collected MTADS data at PBR N-9 and N-10 regarding barbwire fence crossing the middle of the targets	Fence clearly discernable from ordnance targets.
Maintenance	System mount points, hardware, and component inspection	Observations and documentation	Minimal wear and tear.

* Ordnance defined as intact ordnance or major UXO-related scrap.

4.2 Performance Confirmation Methods

Accurate estimation of two of the system performance criteria, i.e. ordnance detection and false positives, are dependent largely on the method of post-survey excavation used. For the Laguna survey, a large number of ground MTADS anomalies were excavated in a 100m x 250m grid in area N-10, and in a 90m x 230m grid in area N-09. In both cases, the zones were well inside the main target area, so the helicopter anomalies are not discrete. Only a few anomalies were dug outside the densely populated target area grid. Such data do not permit accurate estimates of the system's probability of ordnance detection. To determine this number, we used a subset of dig results from the densely populated target area.

4.3 Data Analysis, Interpretation, and Evaluation

The ORAGS-Arrowhead magnetometer system does not distinguish within the numerous features mapped between UXO and ferrous scrap without interpretation. The total field and analytic signal maps provided in this report depict bombing targets (areas of high ordnance density), infrastructure (fences or larger items or areas of ferrous debris associated with human activity), and potential UXO items (discrete sources). Those responses, interpreted as potential UXO, will likely also include smaller pieces of ferrous debris. Additional analysis and interpretation of the survey results are included in this final project report.

Positional accuracy

We estimated positional accuracy by comparison of predicted dig locations with actual dig results from a statistically significant number of items that were excavated in areas N-09 and N-10. There were 192 items classified as UXO-fragments in the excavated grid in N-09 that were within 2 m of an ORAGS-Arrowhead pick location based on analytic signal peak value. For these items, the mean distance between predicted dig location and the location of the actual item excavated (the mean miss distance) was 90 cm. Average positional accuracy at site N-10 was slightly worse than at N-09. In 240 samples, the mean miss distance was 110 cm. Taken together the average miss distance for the two sites is 101 cm. It is clear from the relative positions of airborne and ground MTADS anomalies in Figure 4.17 that these data contain no systematic offset.

A small portion of the 101 cm average offset is a result of the picking algorithm that chooses the analytic signal peak as the predicted item location. Target location based on magnetic dipole inversion yields marginally better results. At 15 targets where magnetic dipole inversion was used to predict the item location, the average miss distance was 94 cm, only 7 cm less than with analytic signal peak location. This result implies that most of the offset is due to the GPS positioning system, not the processing algorithms.

Results from the calibration site show poorer positional accuracy than at either survey area N-9 or N-10. Figure 4.1 shows the locations of the analytic signal peaks. The average distance between the analytic signal peak and the position of the emplaced item was 2.22 m for six test locations, with a minimum miss distance of 1.27 m and a maximum of 2.97 m. The larger miss distances at the calibration site are possibly a result of combining the errors from the calibration site survey using the Trimble ground GPS unit (Trimble location error~1 to 1.5 m) and the errors from the helicopter GPS system (error~1m), and as such do not properly assess the accuracy of the ORAGS Arrowhead system.

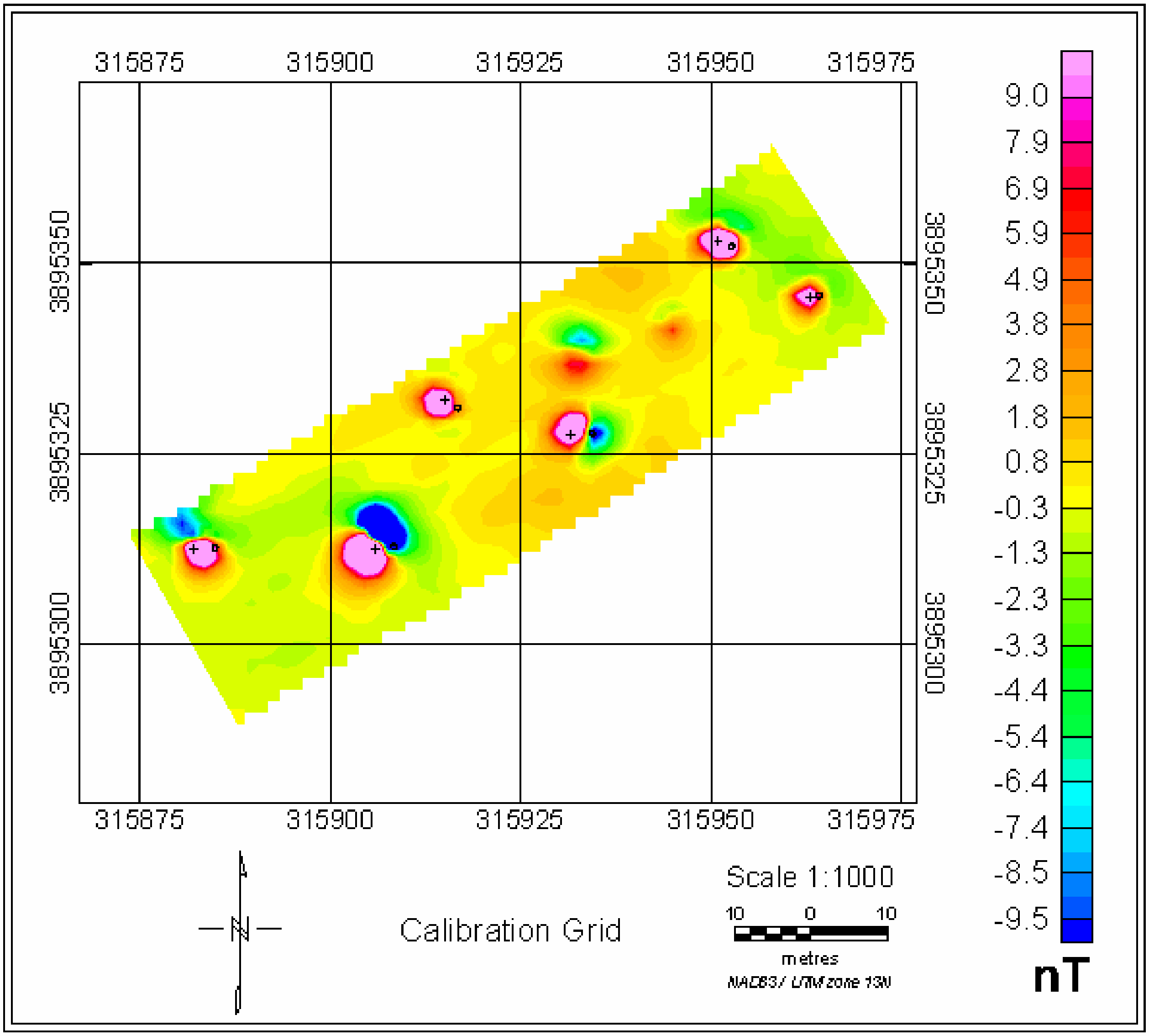

Figure 4-1. Total magnetic field at nominal height of 2m above calibration grid. '+' symbols indicate airborne analytic signal peak values; circles indicate location of test items.

Sensitivity

In the 90m x 350m area in N-10 where the vast majority of digs were conducted, the practical limit at which the ORAGS-Arrowhead system was able to consistently detect UXO fragments is at a peak-to-peak total field anomaly amplitude of about 5 nT. Above this limit, most excavated anomalies containing UXO fragments were detected by the Arrowhead system. Below 5 nT, few excavated anomalies were detected by the Arrowhead system, or conversely, few Arrowhead anomalies less than 5 nT peak-to-peak were associated with ordnance-related fragments.

The excavated sub-area in N-09 produced similar results, but at a slightly higher threshold. The cutoff at which Arrowhead anomalies coincided with UXO fragments was 7-8 nT. This discrepancy could be caused by a masking effect of more magnetic geological material in the soil at N-09.

At the calibration site, described below in greater detail, the smallest single target was a 2.7 kg (6 lb) M-38 fragment emplaced at the ground surface. This target produced a peak-to-peak total field anomaly of 33 nT in a low altitude flyover (~1.5 m AGL). Under a dipolar source approximation, this would imply that at a target-sensor offset of about 2.5 m, the 2.7 kg target should produce a peak-to-peak anomaly of about 7 nT, and therefore still be detectable. At 3 m target-sensor offset, the 2.7 kg item would produce only a 4 nT anomaly, and might not be detected above background noise levels.

Figure of Merit

For low frequency compensation noise, the Figure of Merit (FOM) provides a measure of the residual aircraft signature after compensation. The FOM is calculated as the sum of the remaining peak-peak noise after correction in each of the twelve parts of the compensation flight.

$$FOM = \sum noise_{ij}$$

where noise = average residual peak-peak deflection,
and i = cardinal direction (N, S, E, W)
and j = maneuver (pitch, roll, yaw).

Perfect compensation would produce a FOM equal to 12x the system noise floor. For fixed wing operations, a typical compensation will produce a FOM of 1nT. Boom-mounted helicopter operations typically produce a total field FOM of 2-10nT. The FOM is highly dependent on the particular aircraft used, and can vary by an order of magnitude even with the same type of aircraft. The ORAGS-Arrowhead system when mounted on a different Long Ranger helicopter has produced an FOM as low as 2.6 (at Badlands Bombing Range, ESTCP Final Report . This compares favorably with the lowest FOM of ORAGS-Hammerhead system, 3.8 using the same helicopter. However, the Long Ranger helicopter used in the Laguna survey was not as magnetically clean as the previous helicopter, and this is reflected in an FOM of 11.8 (Table 4.2). This FOM implies that it would be difficult using this helicopter to detect anomalies smaller than about 1 nT (11.8/12). Indeed, 1 nT appears to be the approximate limit of detection in maps showing the residual total magnetic fields from areas N-09, N-10, and N-11.

Table 4.2 Figure of Merit computations

	Np	Nr	Ny	Ep	Er	Ey	Sp	Sr	Sy	Wp	Wr	Wy	total
m1	0.27	0.71	0.17	0.49	1.56	0.35	0.83	1.35	0.35	0.48	0.53	0.26	7.35
m2	0.65	2.01	0.57	0.93	3.04	0.63	1.63	2.88	0.71	1.14	2.15	0.95	17.29
m3	2.59	1.29	0.48	2.14	0.61	0.25	0.83	0.26	0.3	0.77	0.95	0.28	10.75
m4	2.84	1.05	0.5	1.91	0.5	0.25	0.79	0.23	0.25	1.29	0.86	0.35	10.82
m5	2.89	0.42	0.56	1.41	0.72	0.31	0.81	0.22	0.24	1.72	0.58	0.25	10.13
m6	2.4	1.12	0.51	0.92	0.81	0.27	0.95	0.36	0.26	1.88	0.56	0.18	10.22
m7	2.33	2.73	1	0.7	1.22	0.6	0.71	2.63	0.6	1.85	3.48	0.78	18.63
m8	1.09	1.53	0.57	0.22	0.34	0.31	0.28	1.27	0.23	0.88	1.78	0.44	8.94
ave	1.88	1.36	0.55	1.09	1.10	0.37	0.85	1.15	0.37	1.25	1.36	0.44	11.77

Calibration Site

A test grid or calibration site was established to verify the system response to expected UXO items under local geologic conditions. A 100m x 25m area was established on a topographically flat region near the N-10 impact area. The location of the grid was chosen based on suitability of the topography and absence of significant vegetation and metallic debris. The dimensions of the grid were chosen to represent a double swath width of the ORAGS helicopter array. Iron stakes were place at the southwest and northeast corners of the grid, and plastic highway placards were positioned for the pilot's visual reference.

Prior to seeding any target items (other than the iron stakes), the area was surveyed with a Geometrics G858 magnetic gradiometer and real-time DGPS navigation system. The lower sensor was positioned approximately 0.45m above the ground, with the upper sensor 0.60m above the lower. Positions provided by the navigation system were adjusted for the 1.35m separation between the GPS antenna and the magnetometers before gridding the magnetic data. The total magnetic field data were processed to remove diurnal magnetic responses.

The results showed low levels of ferrous debris over the grid. We attempted to place targets at a sufficient distance from the clutter to create a distinct anomaly. Six locations were seeded with inert ordnance items obtained from a local stockpile at S-12. Four locations were individual M-38 practice bombs (ferrous metal casings only) at varying compass orientations. Location five included one M-38 practice bomb casing with scattered debris. Location six included scattered debris only. The positions of these items were measured using a Trimble single phase GPS backpack system with real time differential correction. The accuracy of the Trimble GPS measurements was 1 to 1.5 m. The area was then resurveyed with the same Geometrics instrument as was used in the pre-seed survey.

Results of the pre- and post-seed surveys are shown in Figures 4.2 and 4.3. The large unidentified anomaly in the pre-seed survey data represents a buried source of unknown origin. The list of seeded items (including iron stakes) is presented in Table 4.3.

Table 4.3 – Items emplaced at the Calibration Site including the eight inert ordnance casings (or pieces of ordnance) and two iron stakes.

Easting	Northing	ID	Description	Angle	Weight (lb)	Length (in)	Diam (in)	Notes
315963.16	3895364.56	NE	corner	*	*	*	*	
315975.92	3895343.17	NW	corner	*	*	*	*	
315890.54	3895292.60	SW	corner	*	*	*	*	
315876.97	3895314.07	SE	corner	*	*	*	*	
315884.84	3895312.65	T-1	M-38	150	6.00	32.00	7.50	
315908.33	3895312.81	T-2	M-38 w tail fin	0	7.50	43.00	7.50	
315916.74	3895331.00	T-3	M-38 w tail fin	50	10.00	33.00	7.50	
315934.47	3895327.65	T-4	M-38 w tail fin	100	9.00	35.00	7.50	
315952.72	3895352.22	T-5	M-38 no tail fin	170	3.50	31.00	7.50	M38 badly decomposed
315954.50	3895352.99	T-5a	tail fin, fin assembly	*	3.00	17.00	10.00	72” from M38
315953.59	3895353.98	T-5b	fin assembly	*	1.00	10.00	5.00	69” from M38
315952.40	3895354.03	T-5c	2 tin cans, 7 disks	*	2.00	24.00	24.00	69” from M38, scattered on 24” circle
315951.24	3895353.54	T-5d	fin assembly, metal sheet	*	1.00	12.00	12.00	79” from M38, scattered on 12” square
315951.16	3895351.68	T-	2 fin	*	1.50	15.00	4.00	72” from

		5e	assemblies					M38
315953.64	3895349.83	T-5f	tail fin	*	2.00	8.00	8.00	102” from M38, moved by cow
315964.25	3895345.76	T-6	tail, 3nose, flange, 3det	*	14.00	60.00	60.00	scattered over 60” circle, wt is total

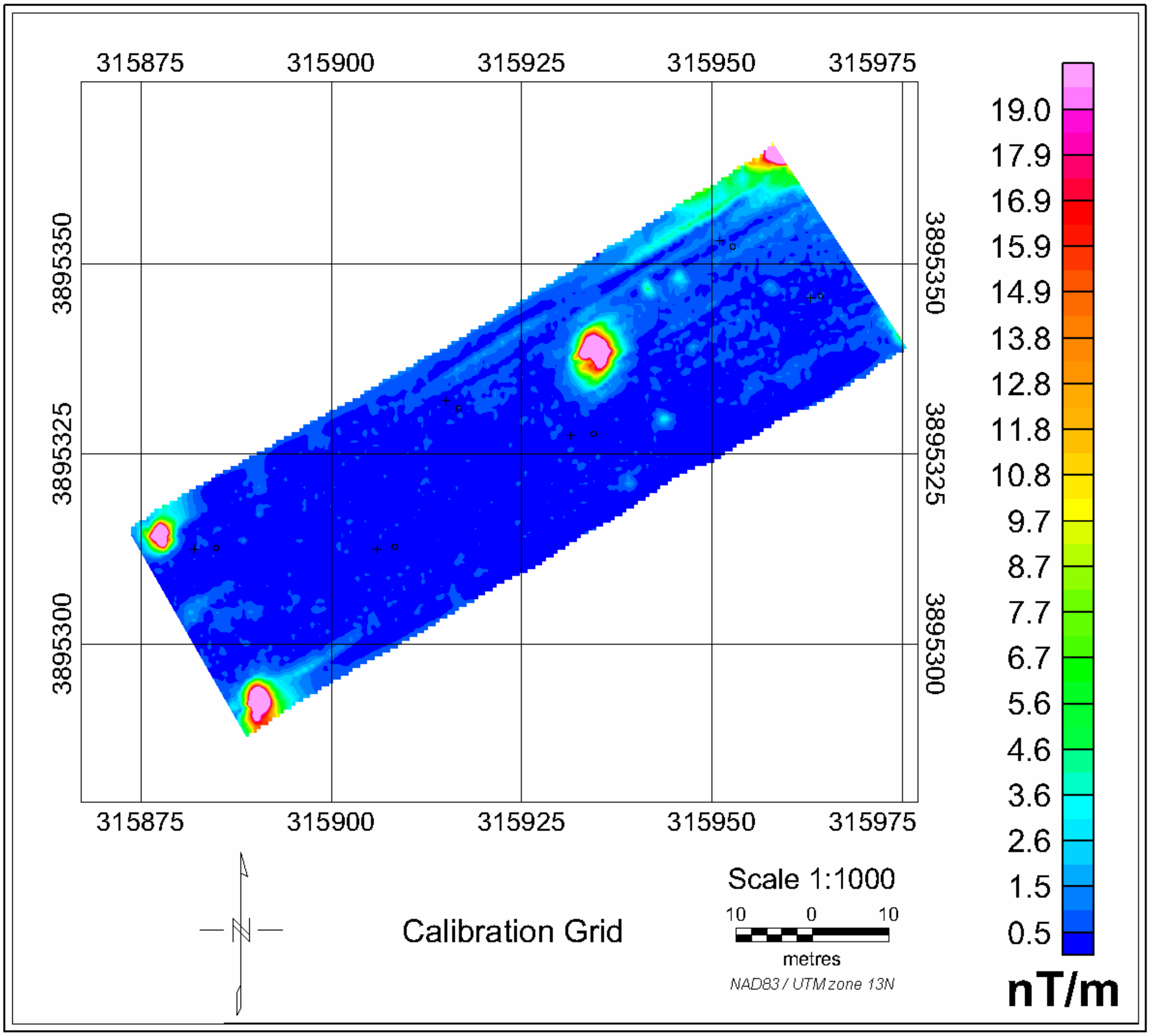

Figure 4.2 Pre-seed ground survey, analytic signal. Circles indicate airborne analytic signal peak values from subsequent emplacement of test items; '+' symbols indicate location of the test items.

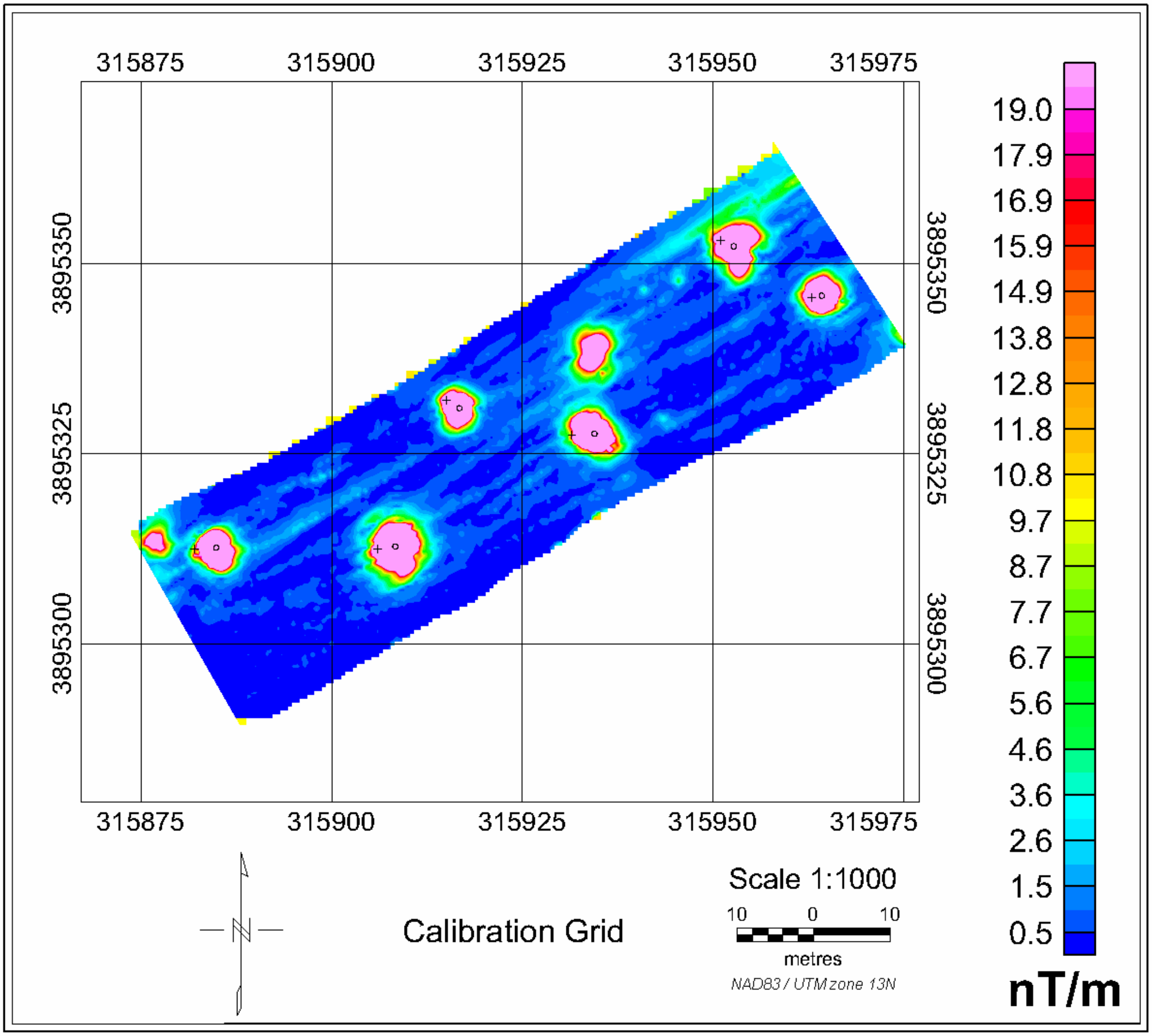

Figure 4.3 Post-seed ground survey, analytic signal. Circles indicate airborne analytic signal peak values; '+' symbols indicate the location of test items.

Area N-09

Area N-09 is a 2 km x 2 km square centered over a bombing target. Lines were flown in an east-west direction, and completely covered a 300 m wide swath in the central portion of the target with a 12m flight line separation. Lines were more sparsely spaced outside the central zone (48 m flight line separation) in order to get a clear indication of the extent of the target without the necessity of flying dense line spacing over the entire 4 km^2 area. Surface fragments indicated that the most likely type of ordnance to be encountered were M-38 practice bombs. In the zone of complete coverage, the average coverage rate was 146 acres/hour (see digital file 'N09_N10_area_rates.xls' on accompanying CD). This value factors in turn around time at the ends of the lines. Average survey speed along line was 23.5 m/s. The anomalies in the northeast survey area appear to be of geological origin, probably basalt flows near or at the surface. A fence is clearly visible running in a northwest-southeast oriented line. Additional lines were flown in the east-central portion of the grid in order to better define anomalies from UXO scrap material visible at ground surface.

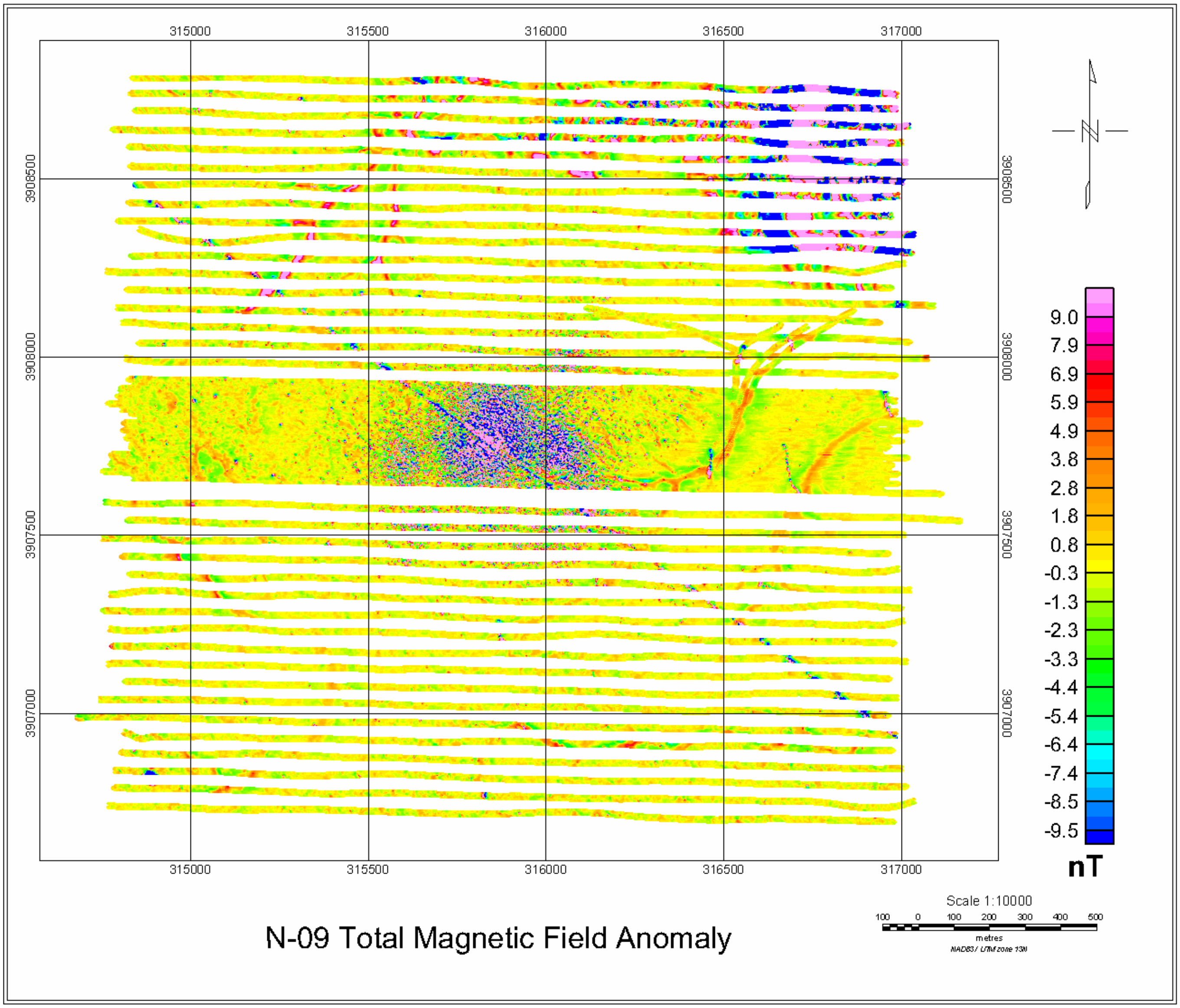

Figure 4.4 Total magnetic field anomaly map, area N-09.

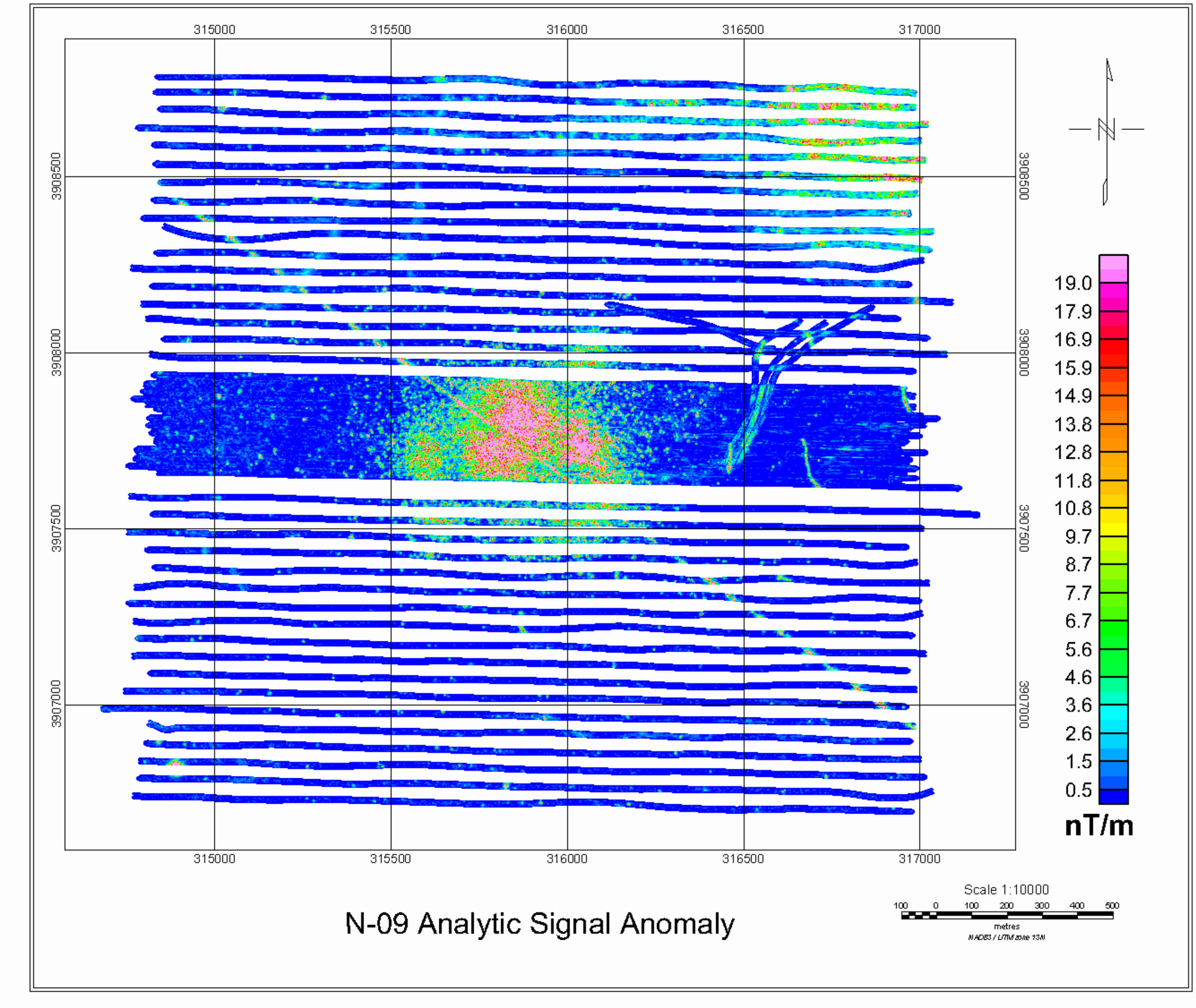

Figure 4.5 Analytic signal anomaly map, area N-09.

Area N-10

Like area N-09, area N-10 is also a 2 km x 2 km square centered over a bombing target. Lines were flown in an east-west direction, and covered the central portion of the target completely. Lines were more sparsely spaced away from the central area in order to get a clear indication of the extent of the target without the necessity of flying dense line spacing over the entire 4 km^2 area. Surface fragments, as evidenced by the debris mound in Figure 4.6, indicated that the most likely type of ordnance to be encountered would be M-38 practice bombs. A fence with azimuthal angle 85 degrees passes through the center of the target. In the central area of complete coverage, the average coverage rate was 141 acres/hour (see digital file 'N09_N10_area_rates.xls' on accompanying CD). This value factors in turn around time at the ends of the lines. Average survey speed along line was 22.8 m/s.

Figure 4.6 Debris mound in area N-10 with ordnance fragments visible.

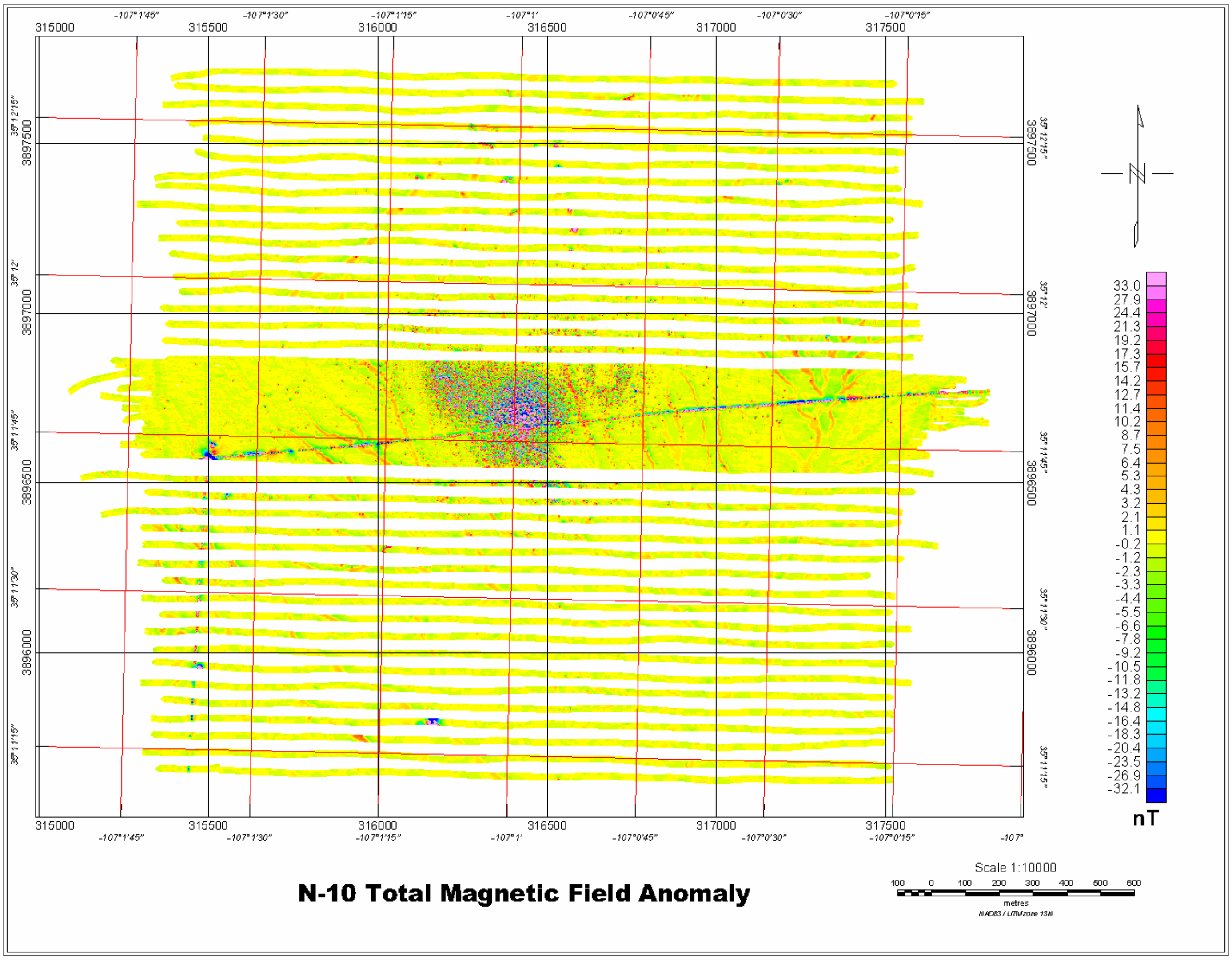

Figure 4.7 Total magnetic field anomaly map, area N-10.

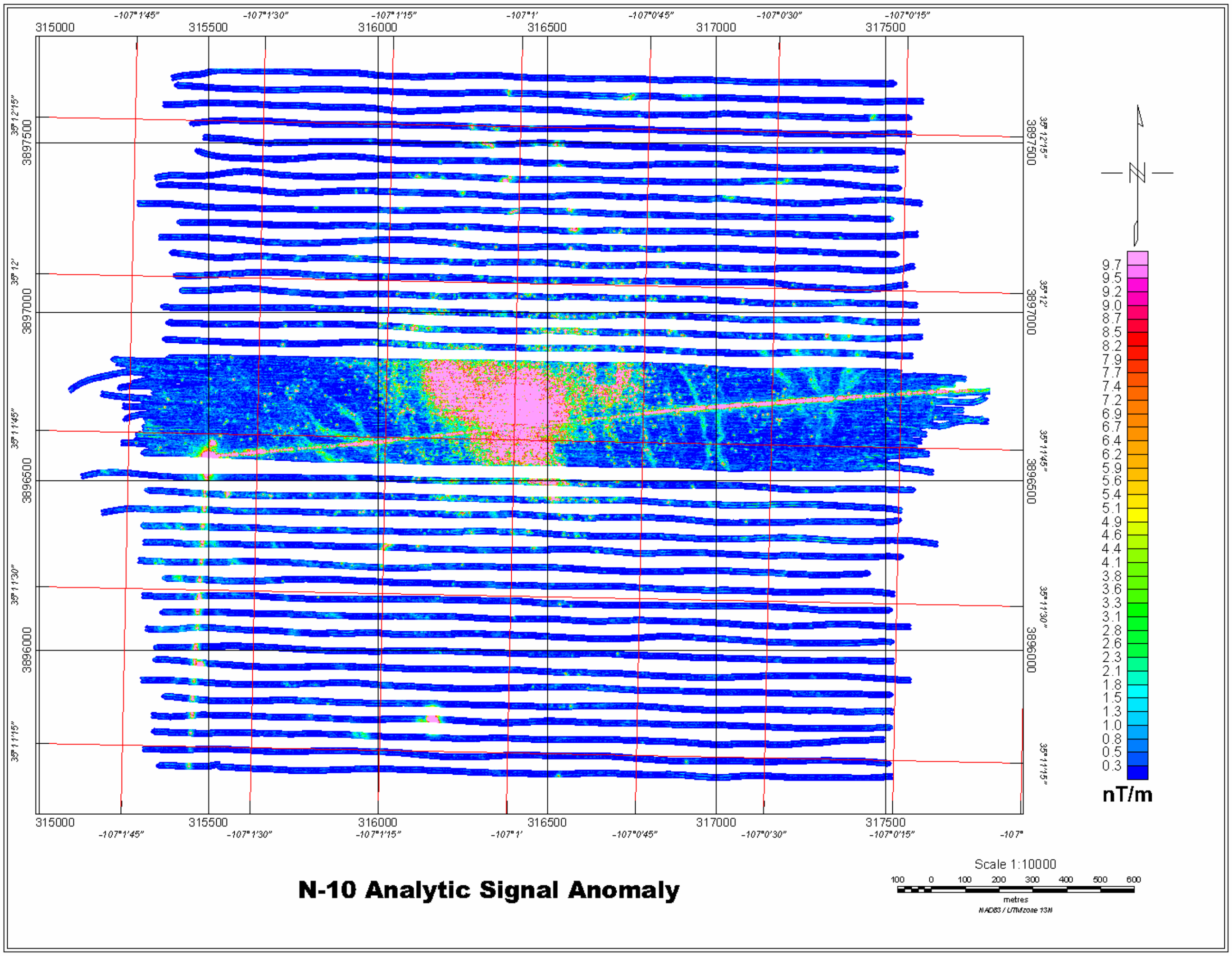

Figure 4.8 Analytic signal anomaly map, area N-10.

Area N-11

Area N-11 is defined by a roughly 2 km x 2 km square area centered over a bombing target. Lines were flown in a north-south direction, and covered the central portion of the target completely, using 12m flight line spacing. Lines were more sparsely spaced outside the central zone, with a flight line spacing of 48m.

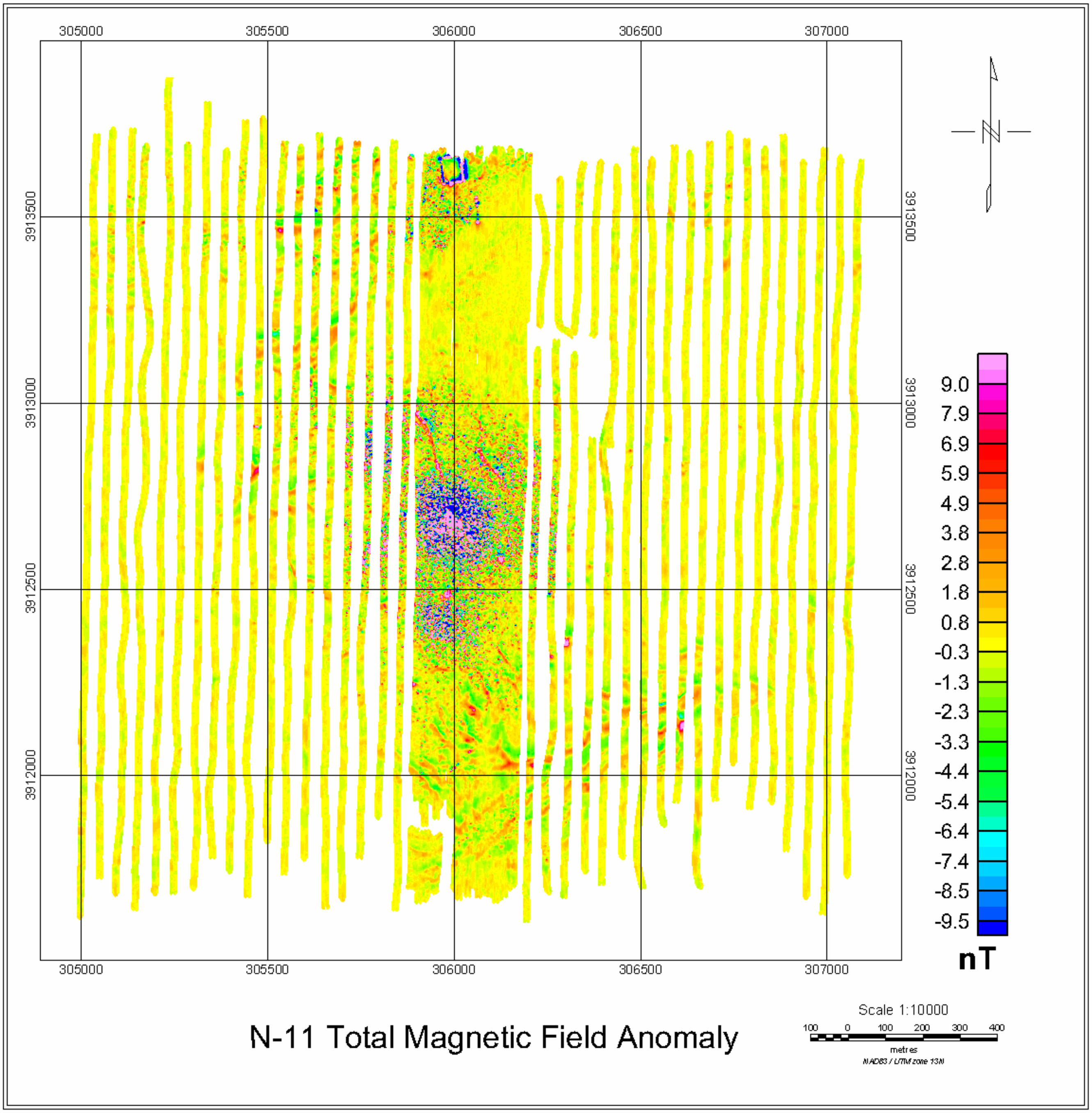

Figure 4.9 Total field anomaly map, area N-11.

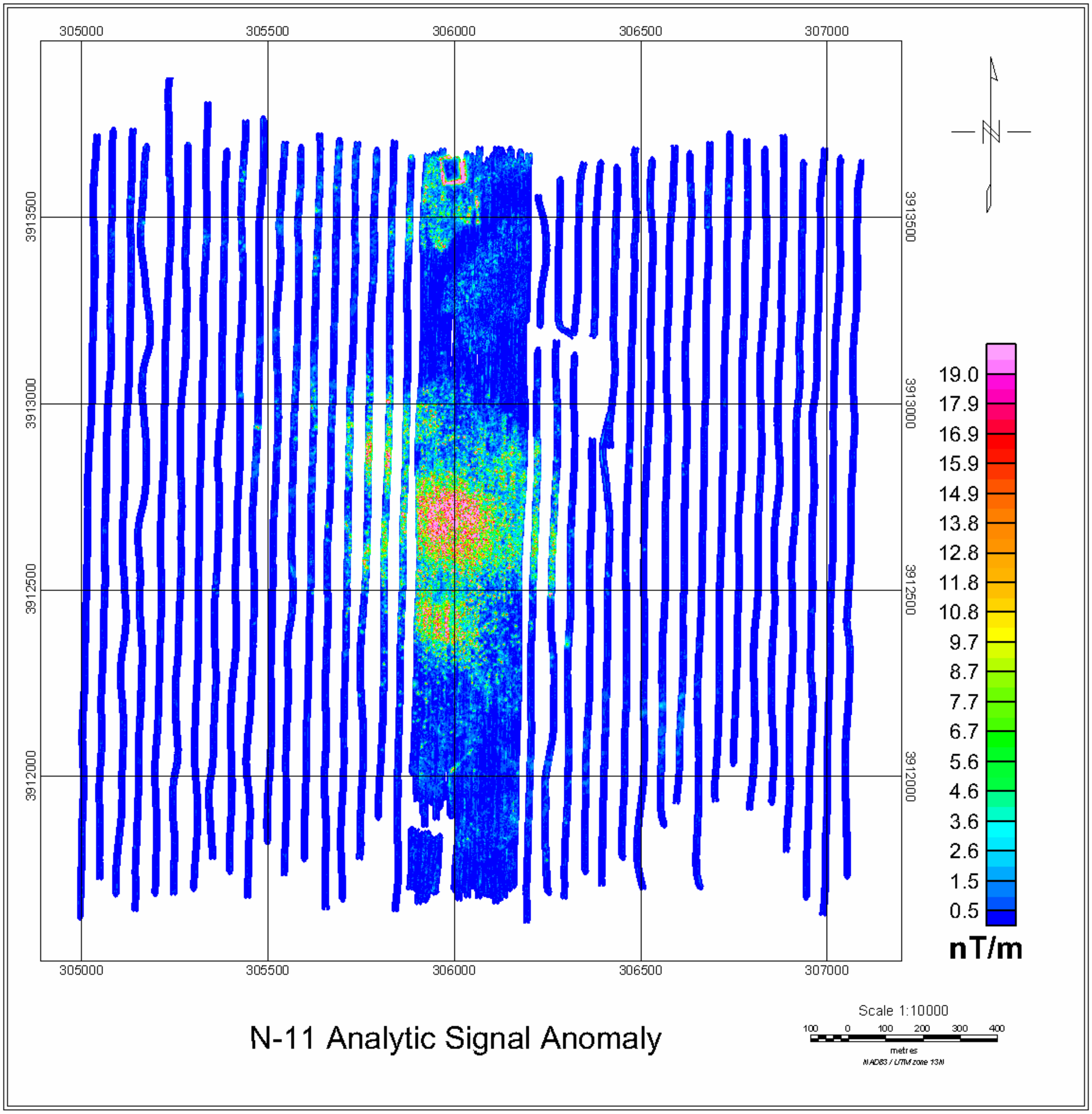

Figure 4.10 Analytic signal anomaly map, area N-11.

Area S-12

Area S-12 is an irregularly bounded 680 acre (275 ha) area centered over a bombing target. Lines were flown in an east-west direction, and covered the central portion of the target completely. Lines were more sparsely spaced away from the central area in order to get a clear indication of the extent of the target without the necessity of flying dense line spacing over the entire area. Surface fragments (Figure 4.11) indicated that the most likely type of ordnance to be encountered would be M-38 practice bombs. The boundary between non-magnetic sediments and near-surface basalt flows can be clearly seen in Figures 4.12 and 4.13, the magnetic field and analytic signal anomaly maps of area S-12, respectively. No reliable UXO-related information was derived from inside the basalt flow area, which covered about 75% of the surveyed area. Although a target is located in the central portion of the survey area, it is indistinguishable from the surrounding basaltic rocks, which commonly produced background distortion in excess of 30 nT.

Figure 4.11 Ordnance derived debris near target in area S-12.

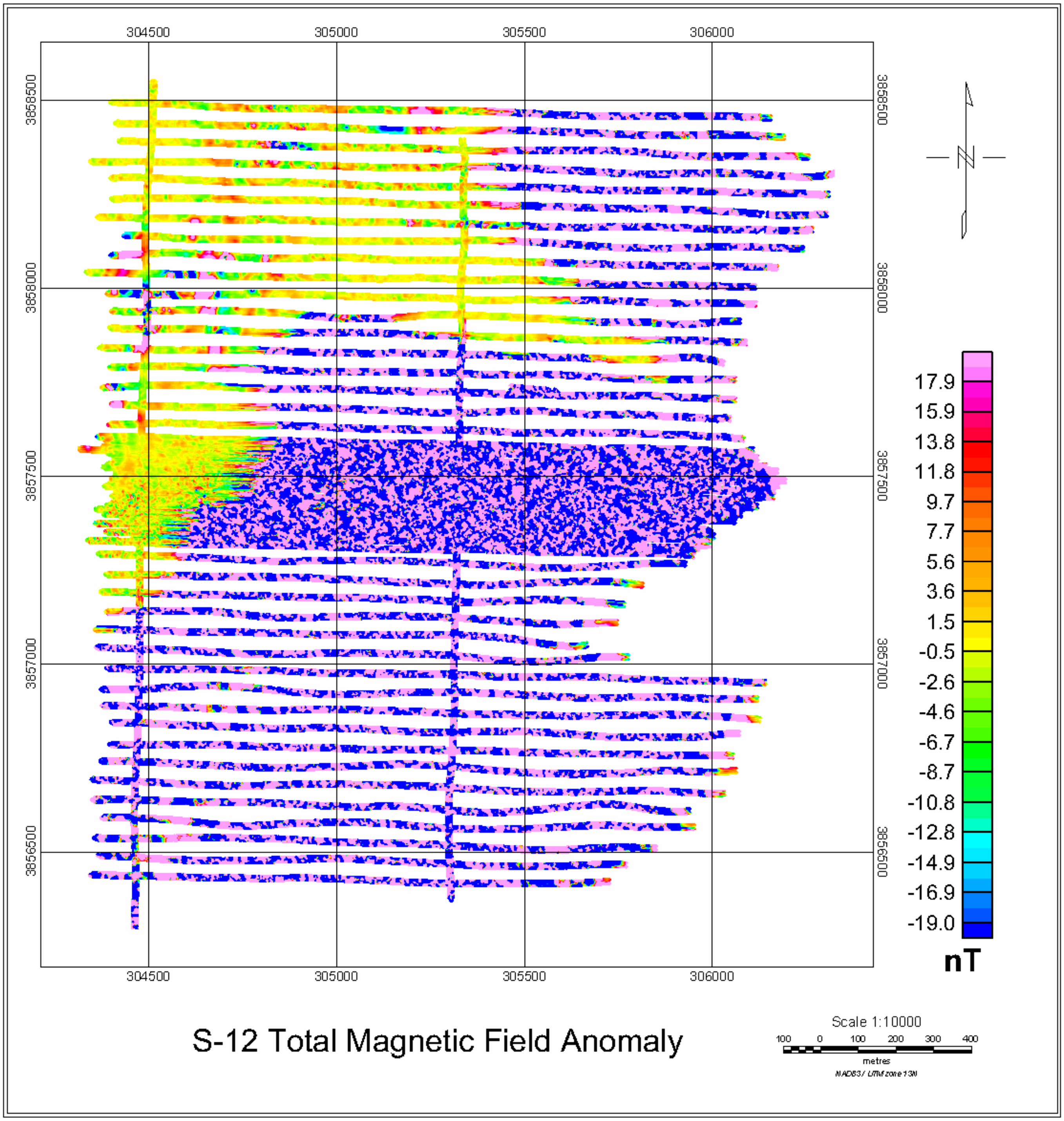

Figure 4.12 Total magnetic field anomaly map, area S-12.

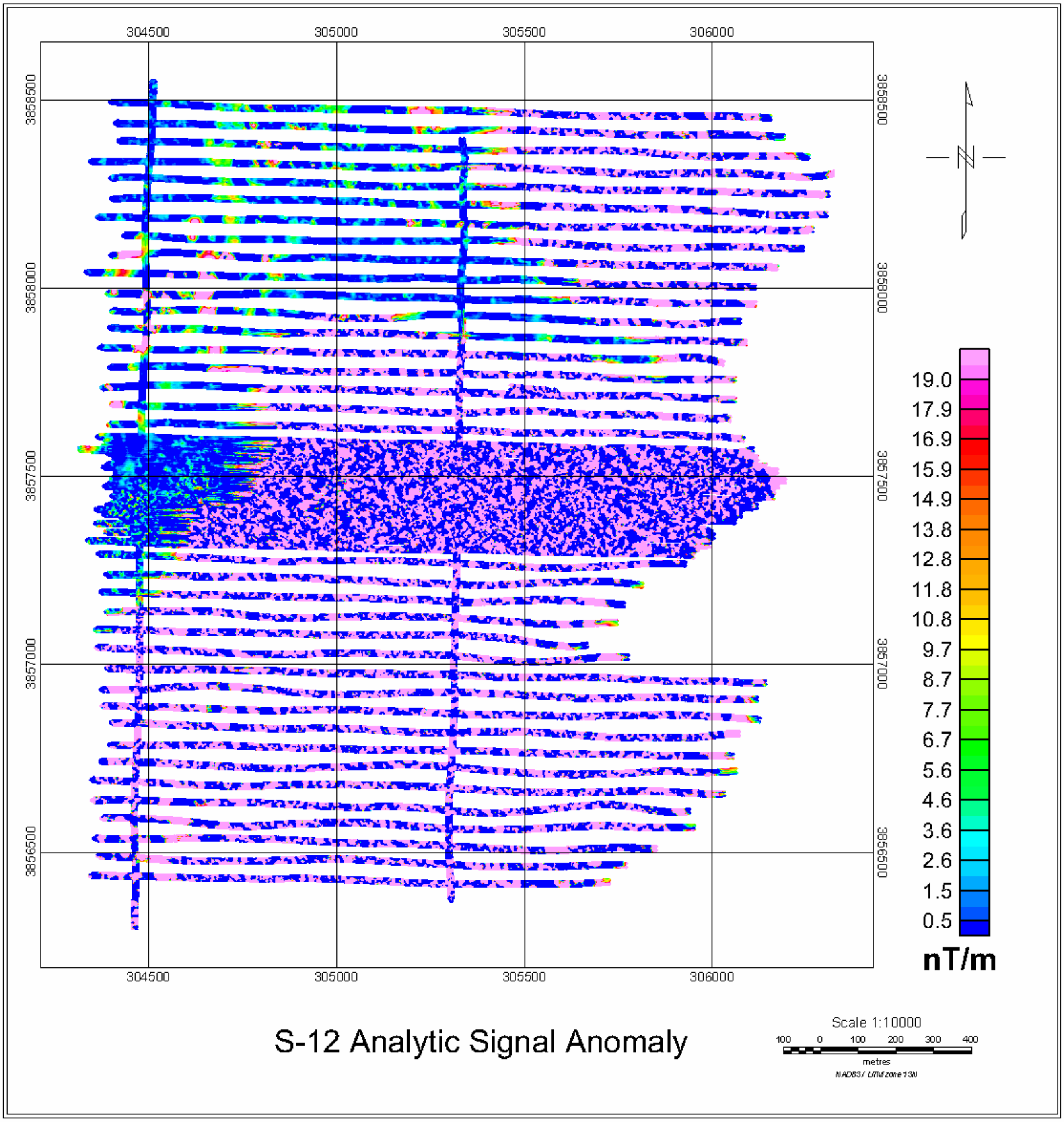

Figure 4.13 Analytic signal anomaly map, area S-12.

Sensor noise levels

Sensors behaved as expected during the demonstration, and sensor noise levels were at or below levels measured in previous demonstration surveys. Figure 4.14 shows raw and processed total magnetic field data for a line passing over the center of the main target in area N-11. Over the target area, anomalies are in the range of 5-60 nT. It is clear from the figure that filters applied in processing do not significantly clip the anomalies, nor does the helicopter induced sensor noise affect anomaly identification at levels of 5 nT or more. Figure 4.15 shows a more detailed view of helicopter noise represented by a 170 m long section of the line in Figure 4.14 that is flown at altitudes of about 20 m above ground level (AGL). Helicopter induced noise averages about 0.6 nT over the section, which is almost entirely removed upon application of filters during processing.

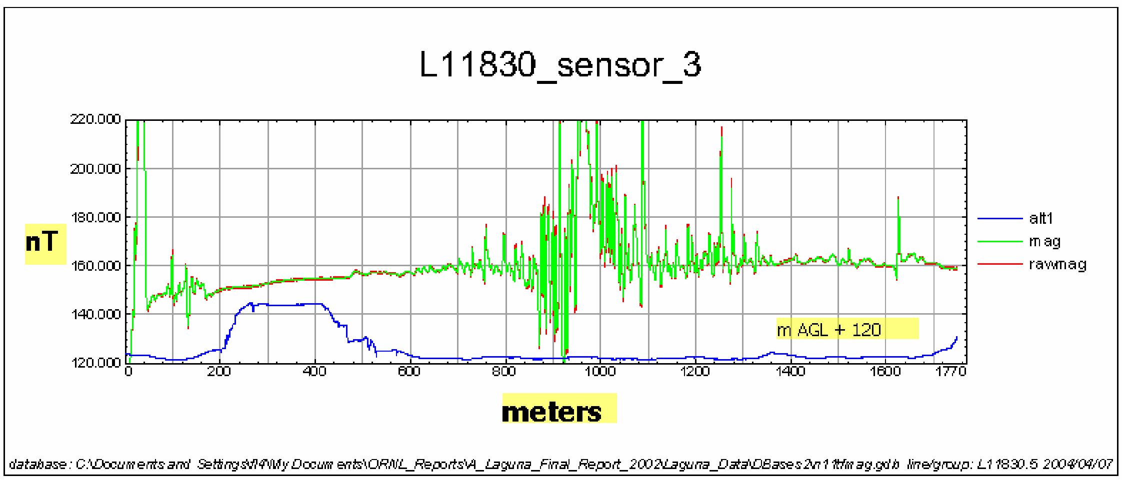

Figure 4.14 Survey line over center of N-11 target area. Altitude varies from 1.5 m AGL to 25 m AGL.

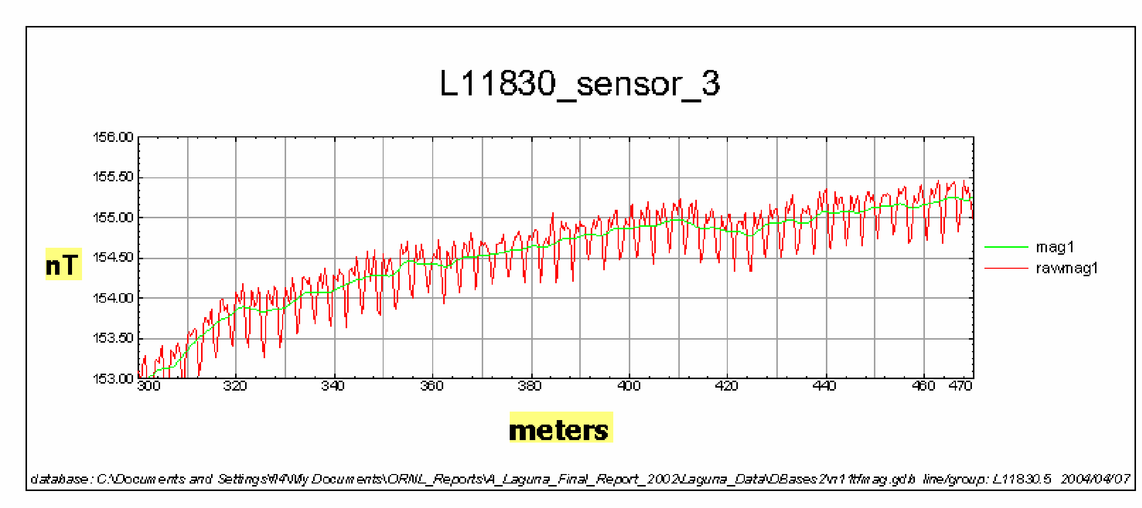

Figure 4.15 Noise levels in raw and processed total magnetic field measured at and altitude of about 25 m AGL.

It is possible to compare noise levels of the eight sensors by applying a high pass filter to the raw magnetic data, then computing the standard deviation of a set of measurements over the same section of line, preferably at an altitude where ordnance anomalies are well-attenuated. If the noise level of one sensor is well-estimated, then by knowing its standard deviation and the standard deviation from the other sensors, the noise levels of the other seven sensors can be computed. Figure 4.16 shows the results of this comparison. Taking data from the high altitude (> 20m AGL) section of the line in Figure 4.14, we find that the noise levels of five of the eight sensors fall near or below a value of 0.6 nT. Only sensors 2 and 7 show substantially higher noise levels. These two sensors are the inboard sensors on the port and starboard rear booms, respectively.

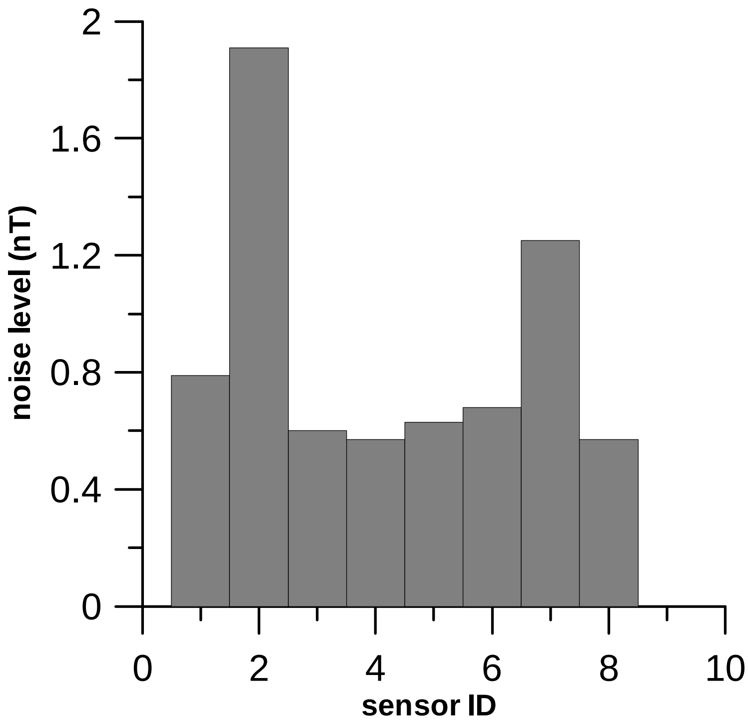

Figure 4.16 Comparative noise levels of sensors 1-8 along high altitude section of line 11830. Sensors 2 and 7, the inboard sensors on the rear booms, have higher noise levels than the other six sensors.

Anomaly evaluation

Anomaly evaluation proceeded after excavations were made in two 90 m x 350 m zones in survey areas N-10 and N-11. The excavation locations were largely derived from ground detections in these two zones from a 1998 MTADS survey. As can be seen in Figure 4.17, some of the excavations do not correspond with sizeable (>20 nT) ORAGS anomalies. We believe these anomalies are too large to be missed by the MTADS ground system or to be false airborne anomalies. We conclude that, given the extended time difference between the two surveys, it is likely that foreign objects have been introduced, and that surface debris may have been moved from its 1998 location, such that anomaly sources are not entirely identical for the two temporally disparate surveys. We therefore located a sub-area in the N-10 excavation zone in which large amplitude ORAGS anomalies are in general agreement with MTADS data. The zone is shown by the rectangular box in the upper right corner of Figure 4.17. In addition, we have performed statistical evaluation of the full data sets for areas N-09 and N-10, and have reported the summary statistics for these areas in Appendix D.

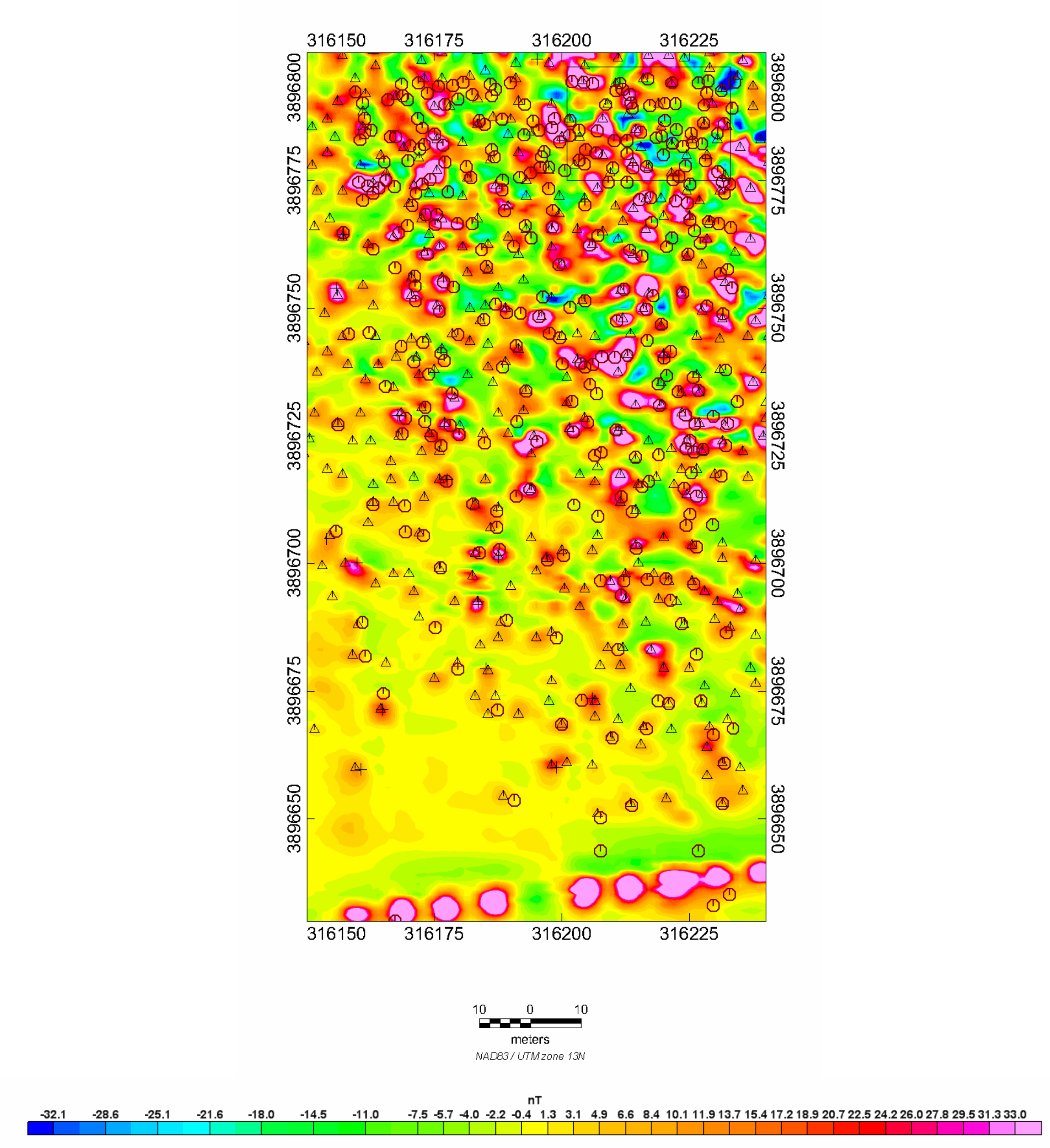

Figure 4.17 Main excavation area at survey site N-10. Circles represent ground MTADS anomalies; triangles represent airborne ORAGS anomalies; and '+' symbols represent airborne anomalies evaluated with DAS inversion software. Statistics were developed on rectangular area in upper right of plot. Total magnetic field anomalies are shown.

In the box, denoted N-10 subplot 1, we made 30 anomaly picks based on the aerial ORAGS magnetic data. Of the locations of these 30 choices, 26 proved to be within 2 m of declared UXO fragments. We claim a detection rate (the detection of intact UXO or major UXO-related fragments) of 87%, and a false positive rate of 13%. Through subplot 1, ground MTADS located 53 ordnance-related items, all listed as UXO fragments. The ORAGS aerial anomaly locations were within 2 m of 35 of the 53 MTADS anomalies, for a ratio of 66%, representing the percentage of aerial anomalies within 2 m of confirmed MTADS anomalies. No reporting was made of anomaly size, so many of the undetected fragments may have simply been too small for detection by the helicopter system. Area N-09 did not have an area similar to N-10 subplot 1, so we were unable to conduct a similar analysis. However, of 335 items dug in area N-09, ORAGS anomaly locations were within 2 m of 221 of the items, resulting in a ratio of 66%. Over both areas, of 631 digs, ORAGS locations were within 2 m of 481, resulting in a ratio of 76%. Again, many of the 150 items not detected by ORAGS may have been too small for detection by a helicopter-deployed system.

More details and data supporting the values quoted above are given in digital form in the Excel file denoted 'Laguna_2002_excavation_summary.xls' on the CD accompanying this report.

4.4 Technical Conclusions

The ORAGS-Arrowhead total field magnetometry system provided data adequate to the task of defining target zones in test ranges having areas on the order of hundreds of hectares. The total field data were precise enough that positions of individual pieces of UXO scrap could usually be identified to within a radius of about 1 meter. Once on site, the ORAGS-Arrowhead system was able to collect data in excess of a rate of 140 acres per hour, a figure that includes turn around time at the ends of lines. Peak-to-peak noise levels in the raw magnetic data were within 1 nT in 6 of 8 sensors. In the two inboard sensors of the rear booms, noise levels exceeded 1 nT, but was less than 2 nT. Once filters were applied to noise induced by the blades and rotor, noise levels were reduced to 0.1-0.2 nT in all sensors. Dig results show that the Arrowhead system detected only about 65-75% of the UXO fragments that were detectable with the MTADS ground magnetic system. However, the sources of most of the airborne anomalies (>85%) proved to be UXO fragments, with a relatively small percentage of no-finds.

5.0 Cost Reporting

Cost information associated with the demonstration of all airborne technology, as well as associated activities, were closely tracked and documented before, during, and after the demonstration to provide a basis for determination of the operational costs associated with this technology. It is important to note that the costs for airborne surveys are very much dependent on the character, size, and conditions at each site; ordnance objectives of the survey (e.g. flight altitude); type of survey conducted (e.g. high-density or transects); and technology employed for the survey (e.g. total magnetic field) so that a universal formula cannot be fully developed. For this demonstration, the following table contains the cost elements that were tracked and documented for this demonstration. These costs include both operational and capital costs associated with system design and construction; salary and travel costs for support staff; subcontract costs associated with helicopter services, support personnel, and leased equipment; costs associated with the processing, analysis, comparison, and interpretation of airborne results generated by this demonstration.

Table 5.1: Survey Cost Assessment

Cost Category	Sub Category	Details	Quantity	Cost[1] (in dollars)
Pre-Survey (Start-up)	Site Characterization	Site inspection (includes travel)	4 days	$8,752
		Mission Plan preparation & logistics	5 days	$8,845
		Calibration Site development (includes pre-seed and post-seed ground-based surveys)	2.5 days	$9,474
	Mobilization	Equipment/personnel transport (includes travel)	2 days	$8,660
		Helicopter/personnel transport (includes travel)	1.5 days (11 hours airtime)	$10,974
		Unpacking and system installation	0.75 day	$4,013
		System testing & calibration	0.75 day	$5,678
Pre-survey subtotal				$56,396
Capital Equipment[2]	Cesium-vapor magnetometers	$122,200 total cost	8 each	$21,996
	GPS	$15,500 total cost	1 each	$2,790
	Booms and mounting hardware	$36,500 total cost	1 set	$6,570
	Orientation system	$16,600 total cost	1 each	$2,988

Capital Equipment[2] (cont'd)	Fluxgate magnetometer	$5,300 total cost	1 each	$954
	Navigation system	$5,200 total cost	1 each	$936
	Laser Altimeter	$7,300 total cost	1 each	$1,314
	Data management console	$31,200 total cost	1 each	$5,616
	Magnetic base station	$15,100 total cost	1 each	$2,718
	GPS base station	$15,600 total cost	1 each	$2,808
	PCs for data processing & analysis	$3,450 total cost	2 each	$621
	Shipping Cases	$4,750 total cost	6 each	$855
	Trailer	$3,600 total cost	1 each	$648
Capital subtotal				$50,814
Operating Costs	Equipment Rental	Spare magnetometers	2 each	$2,540
		GPS equipment	1 each	$10,650
	Data acquisition	Helicopter time, including pilot and engineer labor	21 days (48 hours billed airtime)	$36,548
	Operator labor		21 days	$5,250
	Data processing	Geophysicist	21 days (48 hours billed labor)	$32,340
	Field support/management	Engineer	21 days (48 hours billed labor)	$37,149
	Maintenance	Geosoft software maintenance[3]		$2,237
	Hotel and per diem	Survey team in New Mexico	1 each	$10,542

	Fuel Truck Airport Landing Fees	Remote re-fueling	 21 days 10 days 21 days	$1,035 $525
	Data analysis and interpretation	Geophysicist	15 days	$23,100
	Project management		10 days`	$17,690
	Reporting and documentation		30 days	$46,200
Operating cost subtotal				$202,706
Post-Survey	Demobilization	Disassembly from helicopter, packing, and loading for transport Equipment/personnel transport (includes travel) Helicopter/personnel transport (includes travel)	1 day 2-1/2 days 1.5 days (11 hours billed airtime)	$4,514 $8,660 $10,974
Post-survey Subtotal				$24,148
Indirect Environmental Activity Costs	Environmental and Safety Training	8-hour HAZWOPR (includes the course cost)	1 day	$3,878
Miscellaneous	Department of Energy Federal Acquisition Cost (FAC)	3% of project total; Congressionally-mandated charge for administering the Work-for-Others (WFO)		$10,138

		program		
Total Costs				$348,080

[1]Includes all overhead and organization burden, fees, and associated taxes
[2]Capital costs are apportioned at 20% of the total cost for this project; all capital equipment was used for several projects during the course of the year in which this project occurred
[3]Geosoft software costs include the cost of 1 license and the UX-Detect module. The license cost is apportioned at 20% of the total cost for this project in a similar fashion to the capital equipment costs

6.0 Implementation Issues

6.1 Environmental Checklist

In order to operate, each system must have Federal Aviation Administration approval (STC certificate). The required testing and evaluation performed in Toronto before mobilization to New Mexico has been completed. The report associated with this "shakedown" testing is being prepared under separate cover. In addition, ground crews are required to complete the 40-hour HAZWOPR course and to maintain their annual 8-hour refreshers for operation at most UXO sites.

6.2 Other Regulatory Issues

There are no additional regulatory requirements for operation at either site in New Mexico.

6.3 End-User Issues

The primary stakeholders for UXO issues at the Laguna site in New Mexico are the members of the Pueblo of Laguna Tribe, other residents of Pueblo of Laguna Reservation, and State of New Mexico regulatory authorities. ORNL is currently supporting UXO activities at other sites with the previous generation Hammerhead system. Airborne UXO surveys are being designed to accommodate the limitations and needs of each site. Larger scale surveys have been proposed and discussed with several sites. USAESCH has assisted in efforts to commercialize the existing technology and this has led to shared operation with one contractor for engineering evaluation/cost analysis (EE/CA) activities. As new systems are developed and proven, they will enter into the same cycle of application and commercialization.

7.0 References

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8.0 Points of Contact

Points of contact are given below in Table 8.1.

Table 8.1: Points of Contact

Name	Organization	Phone	Project Role
Steve G. Hildebrand	ORNL	865-574-7374	Division Director
David Bell	ORNL	865-574-2855, 865-250-0578 (cellular)	Project Manager
Bill Doll	ORNL	865-576-9930	Technical Manager
Jeff Gamey	ORNL	865-574-6316 865-599-0820 (cellular)	Operations Manager
Les Beard	ORNL	865-576-4646	Geophysicist
Scott Millhouse	USAESCH	256-895-1607	Project Lead
Jim Piatt	Pueblo of Isleta	505-869-5748	Environment Department Director
Barbara Bernacik	Pueblo of Laguna	505-552-7534	Environment Department Oversight
Dan Munro	National Helicopters	905-893-2727	Helicopter Contractor President

Appendix A: Analytical Methods Supporting the Experimental Design

A.1 Statistically based UXO discrimination

We began investigating statistically-based discrimination methods after an analysis of dig results based on data collected at the former Badlands Bombing Range (BBR) in South Dakota showed statistical differences between ordnance and non-ordnance. In no instance was the statistical difference so strong that a single parameter could predict whether the source of an anomaly was UXO or not, but the possibility for discrimination increased as more parameters were considered. We used a routine developed to our specifications by Geosoft to rapidly identify and characterize anomalies above a given threshold from an analytical signal map. From these peaks we identified the associated magnetic field anomaly and sensor altitude, and computed a number of parameters that could be used directly or otherwise combined as statistically relevant predictors. From this point we used two different approaches for discrimination—a univariate and a multivariate methods.

A.1.1 Univariate method

The univariate method relies on correlations from dig results based on airborne magnetic data collected at two different sites: an East Coast site and BBR. Both sites were geologically 'clean' in that neither contained basaltic rock or magnetic soils that could complicate any interpretations. We chose six parameters showing correlation with known UXO, and at each anomaly location evaluated whether the parameters fell within the range of the majority of known measured UXO. Each of the six parameters was scored zero if the parameter fell outside a specified range, and one if it fell within the range. For example, almost all ordnance in our known sample pool yielded peak-to-peak magnetic anomalies between 1.0 and 80 nT. Any anomaly falling outside this range was scored zero, as non-UXO. The six characteristics were scored and summed, so that items could have a value ranging from 6 (all characteristics in the range of UXO) to zero (all characteristics outside the range for UXO). The six parameters used in the univariate analysis were analytic signal amplitude, magnetic anomaly peak-to-peak magnitude, the distance between the magnetic anomaly peak and low, the ratio of the positive magnetic anomaly lobe to the peak-to-peak magnitude, the estimated source depth, and the angle between magnetic north and the line connecting the positive and negative lobes of the magnetic anomaly (denoted theta).

A.1.2 Multivariate method

Multivariate analysis should provide more information than the univariate approach described above as long as some or all of the variables are correlated, and if the number of known samples is large enough to obtain reliable statistics. The parameters must also be appropriately normalized to remove the effects of different magnitudes for the given parameters. We derived a vector of standard mean parameters $\boldsymbol{\mu}_0$ from a set of measurements over known ordnance items, and compute the symmetric covariance matrix $\mathbf{S}$ from the covariances computed for the different variable combinations. The statistical similarity between the known ordnance and the parameter vector **x** associated with an unknown is given by the Mahalanobis distance (Swan and Sandilands, 1995)

$$D = \{(\mathbf{x} - \boldsymbol{\mu}_0)^T \mathbf{S}^{-1} (\mathbf{x} - \boldsymbol{\mu}_0)\}^{1/2}. \quad (1)$$

The smaller the Mahalanobis distance the more closely the unknown resembles ordnance from the known pool of items. The vectors **x** and $\boldsymbol{\mu}_0$ each have five entries: analytic signal peak, the magnitude of the negative lobe of the magnetic anomaly, the ratio of the positive magnetic anomaly lobe to the peak-to-peak magnitude, the ratio of the distance between the magnetic anomaly positive peak and the analytic signal peak to the instrument height added to the estimated source depth, and theta, as described in the univariate section. The differences in the variables used in the two methods of analysis occurred because the univariate analysis was done prior to a more complete statistical review of the data, which led to the multivariate approach.

A.2 Model-based inversion of magnetic data as an aid to discrimination

Magnetic fields in the vicinity of UXO can often be reliably estimated using a model based on a magnetic dipole. The MTADS-DAS software (McDonald and Nelson, 1999) is based on this model. MTADS-DAS does not perform discrimination, but rather is an aid to the interpreter, who subjectively performs the discrimination task. MTADS-DAS requires as input a set of coordinates (x,y,z) and a magnetic total field measurement at each coordinate. The software constructs a grid of the total field data from which the interpreter can select individual anomalies as likely UXO targets. The user selects a boundary around the anomaly that includes some area outside the main anomaly, and the MTADS-DAS code searches for a dipole model that best fits the selected data. Output are estimates of the moment of the magnetic dipole, its length, orientation, burial depth, and goodness of fit. From the returned parameters, an experienced interpreter can make a reasonably well-informed judgment as to whether or not the source of the anomaly is intact ordnance, scrap, or non-UXO related.

Appendix B: Quality Assurance Project Plan (QAPP)

At the time of this survey, we were not required to have a QAPP in place, nor had ESTCP published the current guidelines for QAPP documentation (ESTCP Final Report Guidance for UXO Projects, Revision 2, April 2002). We nevertheless developed our own QA/QC procedures that were followed through this and other projects. These fall into three main categories: operational QA/QC, system QA/QC, and data QA/QC.

Under the category of operational QA/QC:

- Site visit preliminary to survey to assess appropriateness of site for helicopter geophysical surveying;
- De-gaussing of helicopter rotor to decrease magnetic noise produced by this component;
- Review of GPS almanac to assess best times of the day for surveying;
- Emplacement of a calibration grid for daily system checks;
- A morning meeting to coordinate each day's activities;
- An evening meeting to review activities and safety issues.

Under the category of system QA/QC:

- Installation of booms under the supervision of the pilot and engineer, and subsequent double-checking of all mounts and bolts;
- Daily helicopter inspection and maintenance by pilot and engineer;
- Ground tests of system after installation (checks to determine if all magnetometers are operating and have been connected in the correct order, and an impulse test to determine the lag between magnetometers and fluxgate);
- An initial check flight after installation.

Under the category of data QA/QC:

- An extensive test flight to evaluate the effects of pitch, roll, and yaw on the magnetometers, from which we can calculate compensation coefficients, and to examine the high altitude noise levels of the magnetometers.
- Daily inspection of diurnal magnetic activity at a base station magnetometer;
- Visual inspection of all data;
- Daily plots of flight path and laser altitude;
- Adherence to the data processing flow, described in section 3.6.6;
- Daily production of digital magnetic maps;
- Archiving of all materials: flight logs, digital materials, and report.

Appendix C: Health and Safety Plan

This document represents the health and safety plan applied to field operations in New Mexico.

C.1 Aircraft Base of Operations

Albuquerque International Sunport
2200 Sunport Blvd. SE
Albuquerque, N.M. 87106
Fixed Base Operator: Cutter Flying Service, Inc.
Phone: 505-842-4184

The base of operations for all aircraft activities was Albuquerque International Sunport. The aircraft were stored and some refueling activities will occur at this location. Other refueling activities will occur remotely through use of a fuel truck provided by National Helicopters, Inc. No direct aircraft support (e.g., housing, fuelling, etc.) is requested from the Department of Defense.

C.2 Communications

Air-to-ground and ground-to-ground communications will occur using two-way VHF radios provided by ORNL and National Helicopters. Radios will broadcast at 118 - 135 MHz. All other communications were via cellular telephones.

C.3 Schedule Constraints and Crew Rest

C.3.1 Schedule Constraints

During aviation missions, activities can occur that are uncontrollable by the survey team and cause a delay of data acquisition. These activities may result in missed data acquisition windows or the loss of entire days of data acquisition.

C.3.2 Crew Rest

Crew rest will follow the guidelines prescribed by FAA regulations. Restrictions are placed on both the pilot's in-air flight-time and duty-time.

C.4 Aircraft

Bell 206L Long Ranger III Helicopter
Color scheme: White with midnight blue and light blue accents
Serial Number: 45784
Tail Number: C-FNHG

National Helicopters, Inc.
11339 Albion Vaughn Road
Kleinburg, Ontario, Canada
Phone: 905-893-2727

C.5 Statement of Risks

Airborne geophysical surveys are designed to be conducted with minimal risk to personnel. Safe operation of the aircraft is the ***direct responsibility*** of the pilot, who will determine the minimum safe flight altitude and local weather conditions for safe flying on an ongoing basis. The mission was flown under all applicable Federal Regulations.

Most ground activities were limited to routine working conditions; however certain field activities will expose personnel to summer heat and prairie wildlife. Precautions against the heat include drinking plenty of water, using sunscreen, and taking breaks as needed. Precautions against the wildlife include wearing hiking (or similar) boots and minimization of exposure to that environment. In addition, the two-man rule was in effect for all on-site field activities.

For additional risk-related information, consult the Operational Emergency Response Plan contained in Appendix B of this document.

C.6 Emergency Notification

Emergency action plans are included in the Appendix of this document. In the event of an emergency, staff will first request assistance, then provide appropriate first aid measures until emergency assistance arrives. As soon as emergency assistance has been obtained, the following people were to be notified in sequence based on availability:

Mr. David Bell, ORNL Project Manager
Cellular: 865-250-0578
Office: 865-574-2855
Dr. Bill Doll, ORNL Technical Manager
Cellular: 865-599-0820
Office: 865-576-9930
Mr. Jeff Gamey, ORNL Operations Manager
Cellular: 865-599-0820
Office: 865-574-6316

Mr. Scott Millhouse, USAESCH Program Manager
Office: 256-895-1607
Mr. Dan Munro, National Helicopter, President
Office: 905-893-2727
Dr. Steve Hildebrand, ORNL Environmental Sciences Division Director
Office: 865-574-7374
Home: 865-966-6333

Each organizational member of the project team is responsible for flow-down of communications within the respective organization in the event of an incident or emergency (e.g. notification of next-of-kin by ORNL Environmental Sciences Division Director if ORNL staff is involved in an emergency situation, etc.). Any member of the project team, in the event of an emergency situation, shall **not** contact persons other than those designated in the above listing.

C.7 On-Site Ground Emergencies

In the event of an emergency that occurs on-site:

1) Telephone local emergency response organizations via 911, if needed.
2) Conduct appropriate first aid.
3) Notify managers, as listed above in sequence. **The ORNL Project Manager has jurisdiction for all on-site emergency activities.** If the ORNL Project Manager is not available, the ORNL Technical Manager has jurisdiction.
4) The pilot has jurisdiction for emergency response when the aircraft is airborne, has crashed (if able), or has an emergency situation on the ground.
5) In the event of a catastrophic accident, the ORNL Environmental Sciences Division Director shall be notified immediately, and included in all response team activities, including communication, emergency response, and reporting.

C.8 Off-Site Ground Emergencies

In the event of an emergency that occurs off-site:

1) Assess the urgency of the emergency.
2) Telephone local emergency response organizations via 911, if needed.
3) Conduct appropriate first aid while awaiting professional assistance.
4) Notify managers, as listed above in sequence. **The ORNL Project Manager has jurisdiction for all off-site emergency activities.** If the

ORNL Project Manager is not available, the ORNL Technical Manager has jurisdiction.

5) The pilot has jurisdiction for emergency response when the aircraft is airborne, has crashed (if able), or has an emergency situation on the ground.

6) In the event of a catastrophic accident, the ORNL Environmental Sciences Division Director shall be notified immediately, and included in all response team activities, including communication, emergency response, and reporting.

C.9 In-Air Emergencies

In-air emergencies were to be handled via standard aircraft emergency protocol, including radio contact with the Rapid City Regional Airport. **The pilot has jurisdiction for all emergency response activities and requirements when the aircraft is airborne.** Follow-up telephone/radio notification to the emergency response personnel listed in Section 11.0 were to be made as soon as possible.

Appendix D: Summary Statistics from Sites N-09 and N-10

The tables shown in this appendix were created from the totality of data in areas N-09 and N-10.

Stat Pick Picks N09		
Type	**Count**	**Error**
Empty	32	0.09
Frag	192	0.90

Stat Pick Picks N09			
number of occurences			
Priority	**Empty**	**Frag**	**NonOrdnance**
1	3	2	
2	5	15	
3	10	46	
4	13	66	
5	1	46	
6		17	

Stat Pick Picks N09			
avg error in meters			
Priority	**Empty**	**Frag**	**NonOrdnance**
1	0.00	1.20	
2	0.14	1.01	
3	0.05	0.94	
4	0.12	0.96	
5	0.29	0.79	
6		0.76	

Stat Pick Picks N10		
Type	**Count**	**Error**
Empty	16	0.28
Frag	240	1.10
NonOrdnance	1	0.00

Stat Pick Picks N10			
number of occurences			
Priority	**Empty**	**Frag**	**NonOrdnance**
1		3	
2		12	
3	3	37	1
4	10	62	
5	3	80	
6		46	

Stat Pick Picks N10			
avg error in meters			
Priority	**Empty**	**Frag**	**NonOrdnance**
1		1.71	
2		1.23	
3	0.17	1.12	0.00
4	0.18	1.07	
5	0.72	1.04	
6		1.15	

Stat Pick Picks N10 and N09		
Type	**Count**	**Error**
Empty	48	0.16
Frag	432	1.01
NonOrdnance	1	0.00

Stat Pick Picks N10 and N09			
number of occurences			
Priority	**Empty**	**Frag**	**NonOrdnance**
1	3	5	
2	5	27	
3	13	83	1
4	23	128	
5	4	126	
6		63	

Stat Pick Picks N10 and N09			
avg error in meters			
Priority	**Empty**	**Frag**	**NonOrdnance**
1	0.00	1.51	
2	0.14	1.11	
3	0.08	1.02	0.00
4	0.14	1.02	
5	0.61	0.95	
6		1.04	

N09 Digs				
Type	**Dug**	**ORNL Found**	**% Found**	**Avg Error**
Empty	35	32	91%	0.09
Frag	221	192	87%	0.90

N10 Digs				
Type	**Dug**	**ORNL Found**	**% Found**	**Avg Error**
Empty	19	16	84%	0.28
Frag	355	240	68%	1.10
NonOrdnance	1	1	100%	0.00

N10 and N09 Digs				
Type	**Dug**	**ORNL Found**	**% Found**	**Avg Error**
Empty	54	48	89%	0.16
Frag	576	432	75%	1.01
NonOrdnance	1	1	100%	0.00

N09 Digs	
Type	**Count**
Empty	35
Frag	221

N10 Digs	
Type	**Count**
Empty	19
Frag	355
NonOrdnance	1

N10 and N09 Digs	
Type	**Count**
Empty	54
Frag	576
NonOrdnance	1

Appendix E: Data Storage and Archiving Procedures

General

Digital data are on the CD accompanying this report. Included are: (1) readme files, (2) a copy of the final report in PDF format, (3) digital copies of the total field and analytic signal maps from each area flown (N-09, N-10, N-11, S-12, and calibration grid) in TIF format, (4) dig lists in ASCII format, (5) geophysical data files in ASCII format, (6) total magnetic field grids sampled into ASCII format, (7) ORNL analysis files in Excel format, and (8) excavation results in Excel format.

Geophysical Data

The data included with this report is ASCII text and conforms to the format described in the "Area_Data_Readme.txt" file on the CD-ROM provided. Files are named according to area surveyed: CALGRID_TFMAG.XYZ, N09_TFMAG.XYZ, N10_TFMAG.XYZ, N11_TFMAG..XYZ, S12_TFMAG..XYZ. Coordinates are UTM Zone 13 N, NAD83 (Continental US).

ASCII text file format is comma delimited in the following order:

Column 1: Easting coord (m)
Column 2: Northing coord (m)
Column 3: Line ID
Column 4: laser altimeter (m)
Column 5: raw magnetic signal (nT)
Column 6: residual total magnetic field (nT)

Dig Lists

The dig list information is saved in an ASCII text format file. Numerous dig lists were required of us during the project. Accompanying this document are ASCII files comprising locations for excavation at sites N09, N10, N11, and S12 on the Pueblo of Laguna, New Mexico. The data from which the choices were made comes from a 2002 ORNL helicopter geophysical survey. The locations chosen are derived from dipole fitting using the MTADS-DAS software, from multivariate statistical analysis, from univariate statistical analysis, and from visual inspection of the raw data. Coordinates are given in UTM Zone 13 N (meters) using a NAD83 (Continental US) datum, as well as in geographical latitude/longitude. For each areas N09 and N10 there are 5 dig lists, described below using site N10 as an example.

N10_DAS1.XYZ—Targets generated using MTADS-DAS software having the highest probability of being UXO, e.g. priority 1*.

N10_DAS2.XYZ—Targets generated using MTADS-DAS software having the second highest probability of being UXO, e.g. priority 2.

N10_MV.XYZ—High probability UXO targets not in the above two lists, and generated from multivariate statistical analysis.

N10_UV.XYZ—High probability UXO targets not in the above three lists, and generated from univariate statistical analysis.

N10_RAW.XYZ—High probability UXO targets not in the above four lists, and generated by visual inspection of maps of the processed analytic signal data.

Area N09 includes locations for 212 excavations, area N10 171 excavations, and area S07 200 excavations. All choices were made based on magnetic total field residual data or analytic signal data derived from the total field residual.

The figures in the column marked 'depth' in the DAS diglists should be interpreted as negative numbers being below ground level.

The four files labeled in the format 'Area_statpicks.XYZ' are choices over the areas of N09, N10, N11, and S12 where helicopter data was collected. Priority is based on multivariate analysis, and anomalies were prioritized from class 1 (highly probable UXO) to class 6 (highly probable not UXO).

The two files labeled N09_subarea_uv_targetlist.XYZ and N10_subarea_uv_targetlist.XYZ are anomaly picks inside the 90 m x 350 m rectangular cells where MTADS measurements and digs were made.

*Area N09_DAS1.XYZ has locations from priorities 1, 2, and 3, as there were too few anomalies classed priority 1 at this site to choose from. N09_DAS2.XYZ has priority 4 anomalies.

Images

Geophysical anomaly maps (total field residual and/or analytic signal) for each area (CALGRID, N09, N10, N11, and S12) are provided as image files in TIF formats. The TIF images have been saved at 200dpi at the scale labeled on each map. These files have the form AreaTF.TIF and AreaAS.TIF.

Excel files

Government excavation results are provided in Excel files labeled: ‘Laguna N10 Dig List with Remediation Results_KP.xls’ and ‘Laguna N09 Dig List with Remediation Results_KP.xls.’ Analysis of these data and ORNL data are provided in the Excel files labeled: ‘ORNL_Laguna_2002_excavation_statistics.xls’ and ‘ORNL_N09_N10_area_rates.xls.’