Phase I Geophex Airborne Unmanned Survey System (GAUSS)

**Topical Report
October 1993 - March 1995**

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March 1995

Work Performed Under Contract No.: DE-AR21-93MC30358

U.S. Department of Energy
Office of Environmental Management
Office of Technology Development
Washington, DC

For

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

**By
Geophex, Limited
Raleigh, North Carolina**

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U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880

By
Geophex, Limited
605 Mercury Street
Raleigh, North Carolina 27603-2343

March 1995

Executive Summary

This document is a Phase I Topical Report that describes the status of our progress in this two-phase research project. The work was performed under contract to the Department of Energy, Morgantown Energy Technology Center (contract DE-AR21-93-MC30358). The objectives of the project are to construct a geophysical sensor system based on a remotely operated model helicopter (ROH) and to evaluate the efficacy of the system for characterization of hazardous environmental sites.

Geophysical surveys of environmental sites provide a nonintrusive means of evaluating subsurface conditions, yet for many sites, conditions are sufficiently hazardous that personnel cannot enter the site or must wear elaborate personal protective equipment. Rapid, digital, stand-off, geophysical surveys are needed for these dangerous sites. The difficulty of developing such survey systems is compounded by the requirement that sensors be close to the ground surface for accurate detection and characterization of small features. A geophysical surveying and analysis system is needed that is cost-effective, accurate, nonintrusive, and promotes personal safety.

The Geophex Airborne Unmanned Survey System (GAUSS) is a geophysical survey system that uses a ROH as the survey vehicle. We have selected the ROH because of its advantages over fixed wing and ground based vehicles. The lower air speed and superior maneuverability of the ROH make it better suited for geophysical surveys than a fixed wing model aircraft. The ROH can fly close to the ground, allowing detection of weak or subtle anomalies. Unlike ground based vehicles, the ROH can traverse difficult terrain while providing a stable sensor platform. The ROH does not touch the ground during the course of a survey and is capable of functioning over water and surf zones. The ROH has been successfully used in the motion picture industry and by geology companies for payload bearing applications. The only constraint to use of the airborne system is that the ROH must remain visible to the pilot. Obstructed areas within a site can be characterized by relocating the base station to alternate positions.

GAUSS consists of a ROH with radio controller, a data acquisition and processing (DAP) system, and lightweight digital sensor systems. The objective of our Phase I research was to develop a DAP and sensors suitable for ROH operation. We have constructed these subsystems and integrated them to produce an automated, hand-held geophysical surveying system, referred to as the "pre-prototype". We have performed test surveys with the pre-prototype to determine the functionality of the DAP and sensor subsystems and their suitability for airborne application. The objective of the Phase II effort will be to modify the existing subsystems and integrate them into an airborne prototype. The efficacy of the prototype for geophysical survey of hazardous sites will then be determined.

The GAUSS DAP consists of an electronic positioning system (POS) which tracks the survey vehicle and measures its coordinates, a telemetry subsystem for communication

with the geophysical instruments, and a base station computer (BC) which receives and processes the position and geophysical data. We have constructed a lightweight magnetometer, and the electronics assembly for a multifrequency electromagnetic induction instrument, both suitable for ROH application. We have utilized off the shelf commercial products where possible to reduce cost and design time.

GAUSS uses commercial spread spectrum radio modems for telemetry between the BC and the survey vehicle sensors. We have selected radios that are capable of digital interface rates up to 19.2 kilobaud. This bandwidth can carry 274 magnetometer data sets per second or 56 dual-frequency electromagnetic data sets per second. These radios utilize an error correcting protocol and require no Federal Communications Commission radio license for use. Error free communication at ranges exceeding 1/3 mile have been verified.

We have selected a commercial optical positioning and ranging system for use as the POS. The instrument was designed for land surveying applications and makes position measurements by reflecting an infra red laser beam from an optical target attached to the survey vehicle. Servo motors direct the beam to track the target while measuring azimuth and depression angles. The unit is able to track at a maximum rotation rate of 10° per second which corresponds to a tangential vehicle speed of 40 mph at a range of 100 meters. Electronic distance measurement circuitry modulates the beam intensity and measures time in flight to determine target range. The positioning system provides angle and range data to the BC using a serial communications port. Position updates are available at a rate of 2 per second. Ranges to 700 meters are measured with accuracy of better than 12 mm. We considered the global position system (GPS) as a candidate for GAUSS positioning, but concluded that present GPS receivers are unable to provide adequate performance at an acceptable weight.

A 50 MHz 80486 desk top computer is used as the BC. We selected this machine because it provides adequate power for GAUSS software and has allowed us flexibility to operate from a number of different machines. GAUSS base station software controls all DAP subsystems and performs functions which automatically collect, process, store, and display data from the sensors and the POS. This software is written in C using a real-time multitasking kernel. The kernel allows multiple software tasks to run simultaneously.

We have constructed custom geophysical sensors for GAUSS because suitable commercial sensors are not available. The total field magnetometer consists of a commercial three-axis fluxgate sensor, custom processing electronics, and a CMOS computer with operating software. The magnetometer electronics and sensor weigh 9.5 oz and provide total field readings at a rate of 30.7 samples per second with resolution greater than 1 nT (nano Tesla). For comparison, a representative commercial, optical pump magnetometer is capable of 10 samples per second at a resolution of 0.1 nT, but weighs over 9 pounds (requiring an additional 10 pounds for the battery) which is unacceptable for ROH application.

The electromagnetic induction sensor consists of a transmit and receive coil assembly, a digitally controlled transmitter, a low noise analog receiver with analog to digital converter, and a custom digital signal processing engine. The instrument electronics assembly occupies a single printed circuit board weighing less than 12 oz, and is capable of multifrequency operation in the 400 Hz to 12000 Hz range.

The magnetometer and electromagnetic sensors provide complimentary detection capabilities. The magnetometer can detect ferrous objects at extended ranges. This capability makes it useful for rapid detection and characterization of ferrous targets. We have used magnetometers to locate subsurface objects including drums, pipes, tanks, ordnance, to delineate the boundaries of landfills containing ferrous material, and to characterize magnetic geological features.

The electromagnetic sensor can detect and characterize nonferrous conductive objects and environmental conditions resulting in conductivity discontinuities. We have used the multifrequency electromagnetic data to characterize the size, shape, depth, and orientation of subsurface targets. In addition to the ferrous targets mention previously, we have used our electromagnetic instrument to map landfills not containing ferrous material (detect disturbed earth), to map an unconfined contaminant plume, to locate sites of former underground nuclear detonations, and to locate and characterize subsurface reinforced concrete structures.

We have performed GAUSS test surveys to evaluate the pre-prototype. A site characterization currently requires two technicians, the first performs the role of survey vehicle, the second monitors the GAUSS graphics display and directs the survey. During the survey, a site map is displayed on the video monitor. As the sensor is moved across the site, geophysical and positional data are automatically measured at a rate of 2 sets per second. The data are collected and processed by the base station computer and then displayed in real-time. The display shows the path of the sensor on a color site map which indicates the value of geophysical data at each point. At the conclusion of the survey, the complete survey data-set is available for post-processing and documentation.

Geophex has constructed a 1/4 acre geophysical test site for instrument evaluation. The site features buried objects placed at known depths and orientations. During a representative magnetic survey at this location, two technicians collected 2274 data points with 25 minutes of effort. A manual survey was performed at the same site for comparison. Two operators collected 725 data points after 195 minutes of effort. Use of GAUSS resulted in a 24-fold increase in survey efficiency versus the manual method.

During tests of the GAUSS pre-prototype, we demonstrated the ability of the POS to automatically track a sensor-carrying survey vehicle as it moves along a random path. We determined that the DAP can simultaneously collect, record, and graphically display positional and geophysical data while the survey vehicle carries a sensor in random motion. We performed site characterizations using the magnetometer and the electromagnetic instrument which demonstrated their ability to collect high quality

geophysical data from a moving vehicle. Surveys were conducted at a realistic site in which nearby structures and objects contributed background noise that competed with the target anomalies. We devised and implemented data filters which successfully removed the long wavelength interference effects of the structures. The filtered data were used to locate and characterize buried targets. These test results indicate that the pre-prototype system is capable of efficient assessment of sites in scenarios emulating airborne surveys.

Geophex maintains and flies three model helicopters including a Schoonard X-CELL 60 capable of carrying a 15 pound maximum payload. Other users of the X-CELL 60 routinely use of the helicopter to carry payloads of up to 10 pounds in sorties of 25 minute duration. To guarantee flight performance, we have designed the GAUSS instrumentation package to weigh less than 5 pounds.

The cost of all GAUSS hardware systems is less than \$50k. For comparison, a single hand carried optical magnetometer costs 10\$k. Labor costs for data acquisition and data processing will dominate the budget for site characterization. The automatic data collection and processing facilities of GAUSS will result in labor savings over traditional survey methods. Savings are magnified for operations at hazardous locations.

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List of Acronyms

A/D	analog to digital
BC	base station computer
BIOS	basic input output subroutines
Bx	reference or bucking
C/A	coarse acquisition code
CMOS	complimentary metal oxide semiconductor
CPU	central processing unit
DAP	data acquisition and processing system
DOS	disk operating system
DSP	digital signal processing
EDM	electronic distance measurement
EM	electromagnetic induction
FC	flight computer
GAUSS	Geophex Airborne Unmanned Survey System
GPS	global positioning system
OEM	original equipment manufacturer
OEW	ordnance and explosive waste
PAL	programmable array logic device
POS	position measurement system
PWM	pulse width modulation
ROH	remotely operated helicopter
RS-232	a serial interface port standard
Rx	receive
Tx	transmit
UART	universal asynchronous receiver transmitter (serial port)
UXO	unexploded ordnance

1.0 Introduction

Geophex has performed the work reported in this document under a contract (DE-AR21-93-MC30358) from the U.S. Department of Energy, Morgantown Energy Technology Center.

1.1 Background

Geophysical surveys provide a nonintrusive means of evaluating subsurface conditions at environmental sites. Subsurface objects including drums, pipes, filled trenches and pits, tanks, and leach fields can be detected and characterized using geophysical sensing techniques. To obtain complete characterization with currently available technologies, technicians must walk and stand at numerous locations throughout the site. These personnel are placed at risk because the survey procedure results in the chance of interaction with hazardous material such as buried unexploded ordnance (UXO) items, radioactive materials, and hazardous chemicals.

Safety procedures (e.g. personal protective equipment) employed to reduce the risk to personnel, decrease the efficiency of site characterization. During hazardous site assessment, a smaller percentage of the total effort is used in actual geophysical characterization. Time is required for tasks such as formal safety monitoring, decontamination, and site egress. The survey process itself is less efficient due to elaborate protective equipment and procedural precautions. These factors substantially increase the cost of characterization at hazardous locations without eliminating all risk to personnel.

The problems of health and safety, as well as efficiency can be addressed by use of a remotely operated geophysical survey system. In such a system, an unmanned survey vehicle carries geophysical sensors into a hazardous location. A remote pilot remains outside the hazardous site and operates the vehicle using radio control. Values and locations of the geophysical data are processed by an automated data acquisition system which displays data on an off-site monitor. The pilot uses the display to direct the survey vehicle for complete site coverage.

The Geophex Airborne Unmanned Survey System (GAUSS) is a geophysical survey system that uses a remotely operated model helicopter (ROH) as the survey vehicle. We have selected the ROH because it has advantages over alternative vehicles. The ROH has no minimum air speed or minimum turning radius; this allows the ROH to work closer to the ground and nearer to obstacles than a fixed wing vehicle. These flight characteristics allow ROH-carried instruments to detect small features. Unlike ground based vehicles, the ROH can be deployed for surveys of marshes and surf zones and can function over steep or uneven terrain while providing a stable instrument platform. No part of the ROH survey system touches the ground during characterization of contaminated sites. These

advantages of the ROH platform have been recognized and utilized by the motion picture industry for remote cinematography.

Figure 1 depicts a GAUSS survey scenario in which a ROH carries geophysical sensors above a hazardous site. Using GAUSS, two technicians efficiently conduct site assessments at a stand-off distance. The ROH flies at low altitude, allowing the sensors to detect weak anomalies due to small, subtle, or deeply buried targets. Geophysical data and positional data are telemetered to a computer base-station. The data is processed and graphically displayed in real-time on a video display terminal. The display indicates the size, location, and strength of geophysical anomalies. The data is simultaneously recorded to fixed disk and is available for post mission processing and survey documentation.

Figure 1. Conceptual design of the Geophex Airborne Unmanned Survey System (GAUSS) for characterization of hazardous environmental sites.

1.2 Research Objectives

This project is a two phase feasibility study to determine the applicability of ROH carried sensor systems for stand-off geophysical surveying. This report summarizes the Phase I effort in which we have designed, constructed, and evaluated a hand-held sensor system, the "pre-prototype." Our objectives for the Phase I research can be explained in terms of how they support Phase II objectives. The ultimate objective is to apply GAUSS

technology to nonintrusive surveys at Department of Energy hazardous sites. The success criteria in meeting the Phase II objectives are:

1. Demonstrated ability to maneuver the ROH with full GAUSS instrumentation.
2. Demonstrated ability to automatically acquire position and sensor data from the ROH-mounted instruments
3. Demonstrated ability to display in real-time the results of the survey.

During Phase I, we have addressed success criteria 2 and 3. We have designed and constructed a functional data acquisition and processing system (DAP) suitable for ROH application. The DAP measures the position of the survey vehicle, telemeters position and geophysical data to an off-site location, then records and displays the survey data in real time. Additionally we have designed compact sensors which can be used in the ROH system. These sensors have been packaged for hand-carried operation for use with the Phase I pre-prototype system.

We have generated objectives for our Phase I research based on the hardware and software subsystems required for construction of the DAP, and for construction of flight capable geophysical instruments. The requisite subsystems are described next, and are identified in Figure 2.

During a survey, the geophysical instruments make measurements under the control of a flight computer (FC). After processing the raw instrument data, the FC transmits the data to the base-station computer (BC) by radio. The BC simultaneously receives unsynchronized data-streams from the FC and from the position measurement system (POS) which tracks the helicopter location. The position and geophysical data are processed by the BC and displayed graphically in real time. Data is simultaneously logged to fixed disk for post-mission processing.

Based on these requirements, our Phase I research objectives are:

1. Design, construct, and test intelligent, light-weight geophysical sensors having digital output. The sensors must be suitable for ROH-borne application.
2. Acquire a light-weight, two-way digital telemetry system and incorporate a communications protocol featuring error detection and correction capabilities.
3. Acquire and evaluate a suitable, real-time electronic position measurement system.
4. Develop software for remote instruments and for the base-station which performs sensor control, communications, positioning system interface, data recording, error detection, data processing and graphics display functions.

5. Integrate the components to produce a fully functional, hand-carried pre-prototype.
6. Test the capabilities of the pre-prototype and evaluate applicability to an airborne prototype system.

Figure 2. A block diagram illustrating the major hardware subsystems of the GAUSS pre-prototype.

We have successfully completed these six Phase I research objectives. Section 2.0 provides information about the individual subsystems which comprise the pre-prototype. Section 3.0 discusses the capabilities of the overall system and presents results of pre-prototype test surveys.

2.0 GAUSS System Development

The GAUSS pre-prototype consists of five hardware subsystems (telemetry, POS, BC, magnetometer, and induction electromagnetic sensor). In this section, we discuss development of each subsystem. We also present the operational characteristics of the ROH because it is a crucial element development of the prototype system. The pre-prototype hardware subsystems are packaged for operation in a hand-carried system. However, each component has been selected to allow adaptation of the pre-prototype to a ROH-based system.

GAUSS requires substantial software. The FC requires firmware to control the sensors and to communicate with the BC. The BC requires software to perform all DAP functions. Topology and function of the GAUSS software will be presented. The merits of each hardware and software subsystem will be compared with alternative implementations. The considerations used in subsystem design were:

1. Size and weight. The total weight budget for the ROH payload is 8 lb.
2. Performance. GAUSS must be efficient, produce high quality data, and be practical to use.
3. Durability. The hardware must be able to withstand the rigors of daily field use. Software must be robust, able to gracefully recover from data errors.
4. Cost. The system must be affordable, making it a viable alternative to other methods of site characterization. Effort was made to reduce the cost of flight systems which are at risk of damage.

We have used commercial off-the-shelf hardware and software products whenever possible. Use of commercial products reduces development cost, increases system reliability, improves serviceability, allows easier system upgrade, and reduces cost for the production of a moderate number of units. Geophex has constructed custom built components only when suitable commercial products were not available.

2.1 Data Acquisition and Processing System (DAP)

2.1.1 Overview

The functions performed by the DAP are central to GAUSS operation. The DAP must continuously track the location of the survey vehicle. Sensor data and associated position data concurrently arrive at the BC. In real-time, the BC receives, interprets, displays, and stores the data. These DAP functions are automated, requiring no human intervention after system initialization. The DAP subsystems, indicated in Figure 2, will be discussed.

2.1.2 Telemetry

Information transfer is necessary between the FC, located on the survey vehicle, and the BC. The FC communicates geophysical sensor data and status information to the BC. The BC issues configuration commands and status information to the FC. A commercial, spread spectrum RF modem, the Proxim model PL-1, accomplishes the two-way digital communication.

The PL-1 features transparent error detection and correction with interface rates up to 19.2 kilobaud. This rate can carry 274 magnetometer data sets per second, or 56 data sets per second of dual frequency electromagnetic survey data. This performance exceeds any foreseeable system requirements. A point-to-point broadcast mode is used so that additional remote transceivers can be added to GAUSS if required. The radio digital transmission rate is 121 kilobaud so that system performance will not be degraded if additional transceivers are used. The spread spectrum modulation technique uses the 902-928 MHz band which allows high reliability communication with only 0.4 W transmission power. The radios can be used anywhere within the United States without a radio license. We have tested these radios at ranges up to 600 meters, including areas with heavy brush and timber where line-of-site was severely obscured, without loss of data. An unpackaged, single circuit board OEM version weighs 5 oz with antenna and will be used in the ROH prototype.

2.1.3 Position Measurement System

The positioning system constantly tracks the survey vehicle location and reports this data to the BC. We have investigated radio and optical positioning systems to perform this function. Based upon communication with researchers who are developing proprietary positioning systems, we have decided to utilize commercial positioning systems. Ground based radio positioning systems (and acoustical systems) have been ruled out due to complexity since they require 3 to 5 synchronized electronic observing stations. The remaining two commercial alternatives for positioning are the Global Positioning System (GPS) and laser position measurement. We investigated the ability of these two options to meet GAUSS positioning requirements.

We have determined that a nominal update rate of once per second is sufficient since a vehicle moving at 10 mph will travel about 7 ft during this interval. If geophysical data is desired at closer intervals without reducing vehicle speed, GAUSS can interpolate vehicle position between position updates. Even allowing for reduced average flying speeds of 4 mph, we have determined that 3 ft positioning accuracy is sufficient.

We have closely followed the evolving capabilities of commercial GPS products by periodically communicating with sales and technical representatives of eleven major manufacturers. Additional information has been gained by monitoring periodicals which pertain to GPS and its use. We have also communicated with consultants who specialize in integration of GPS systems. Our conclusions regarding GPS systems are summarized:

1. Differential C/A code receivers can determine real-time position on-the-fly at update rates of once per second. Realistic accuracy for these receivers, accounting for multipath and non-optimal satellite geometry, is 2 m rms, 1σ . A significant number of positions will be mis-reported by 6 to 12 ft by these systems. This introduces substantial noise into GAUSS data sets.
2. Use of differential C/A code GPS will place a burden on flight systems since the mobile GPS receiver requires radio communication with a GPS base-station containing differential correction updates. Position calculations are performed at the mobile GPS receiver, so position data must be transmitted back to the BC. It is possible that the FC and the mobile GPS receiver can share a single radio. Overhead for this 4-way communication using two radios is increased since all messages will have to be conveyed in RTCM-SC1004 format. The alternative of flying two radio transceivers is untenable.
3. Differential carrier phase receivers can provide superior accuracy for real-time, on-the-fly applications (50 cm). If phase lock is lost, the receiver must return to an initialization location and reinitialize. Loss of lock is common during ground-level surveys in the Eastern US where trees can obscure parts of the sky. It can also be difficult to maintain lock between buildings, in mountain passes, or near the edge of forests. For this reason, many carrier phase instruments utilize dual frequency receivers. This is a differential scheme and is subject to the radio communications difficulties mentioned previously.
4. Dual frequency receivers can provide real time, on-the-fly positioning. These receivers can also "initialize anywhere;" if lock is lost, the receiver does not have to be returned to an initialization location. The size and weight of these receivers prohibits their use in GAUSS. Communications difficulties are as stated previously.

Present GPS technology does not meet the GAUSS requirements of accurate real-time positioning and compact size. Should shortcomings be overcome in the future, GPS is the preferred positioning system. Advantages are that GPS can be used anywhere in the world and that line of site need not be maintained between the ROH and the base-station. A single GPS base-station can be used for multiple mobile GPS receivers. If communications overhead can be resolved, GAUSS can operate with multiple independent geophysical sensors gathering data simultaneously from different locations.

Laser positioning systems are used in applications such as hydrographic surveying and jet airplane landing studies. Units with high power optical output can range objects at several thousand meters. Lower power units designed for use in land surveying applications can range to several hundred meters. These "total stations" are used for positioning in short baseline hydrographic work. We have studied automatic tracking total stations manufactured by Topcon Corporation and by Geotronics. These systems function by measuring infra red laser light which is reflected from a mobile target. A computer

controlled servomechanism tracks the target and provides azimuth and depression measurements. An electronic distance measurement (EDM) circuit modulates the beam and computes target range by determining optical time-in-flight. We found the Topcon product was able to range at greater distance, using a simpler optical target than the Geotronics unit.

The Topcon AP-L1 optical positioning system is presently used with the GAUSS pre-prototype. The AP-L1 provides position updates at rates up to 2 per second and can range a large prism up to 700 m. The maximum angular tracking rate is 10 per second which corresponds to 40 mph tangential speed at a 100 m range. While the instrument is tracking, ranges are accurate to 10 mm + 2 ppm, and angular errors are less than ± 2 minutes at the maximum rotation rate. The position error for a target traveling at maximum tangential speed at 100 m range is about 10 mm.

The AP-L1 uses a serial port (RS-232) for communication with the BC. The BC issues configuration commands and data receipt acknowledgment messages. The AP-L1 transmits data and status information. Details of the BC/AP-L1 communication were resolved with technical cooperation from Topcon Corporation. If the AP-L1 loses tracking lock during a survey, the instrument enters into a search mode which enables it to automatically reacquire the survey vehicle reflector.

An advantage of the optical positioning system is that only passive reflectors need be carried on the survey platform. The reflectors consume no power from the vehicle supply and because positional data is available at the base-station, no burden is placed on the telemetry system. The system has been tested using various reflectors as targets including reflective tape, plastic "bicycle" reflectors, and precision corner reflectors. The high quality (and heavier) reflectors can be ranged at greater distances but performance is about the same at shorter distances. Accuracy of the optical position data will allow us to compensate the measured geophysical data for variations due to changes of ROH altitude during a survey.

A restriction imposed by optical positioning is that unobstructed line of sight must be maintained between the optical instrument and the reflector (survey platform). This restriction is already in effect because the pilot must maintain a clear view of the ROH to control it. If a portion of a survey site is obstructed from view of the instrument, the instrument can be traversed to a new location and the survey continued. Software can be written to allow re-positioning of the base station while translating the data to the original coordinate system. The translated data can be displayed on the original graphics map.

2.1.4 Base Station Hardware

A 50 Mhz '486 desktop computer running DOS with a VGA color display is used as the GAUSS base station. This machine has sufficient power for the GAUSS system and is a common machine which provides a wide base of systems on which GAUSS can operate. This capability has already been exploited, GAUSS software has been ported to a DOS

laptop computer and used by geologists at Geophex during a commercial geophysical project.

2.1.5 Base Station Software

The BC software ties all GAUSS subsystems together and defines the operational characteristics of the system. The software controls all DAP hardware for the purpose of receiving, processing, storing, and displaying data. We will discuss the structure of the software and considerations regarding the graphics display.

The specific functions performed by BC software can be understood by referring to the DAP hardware subsystems which must be controlled (see Figure 2). Specific tasks are:

1. Receive data packets from the AP-L1 positioning system via UART 2, identify and discard bad data, parse the data and use it to compute Cartesian coordinates of the survey platform.
2. Transmit configuration commands and data receipt acknowledgments to the AP-L1 via UART 2 using error detecting protocol.
3. Receive geophysical sensor data and status data from the FC via UART 1 (radio), parse the packet and format the information, identify and discard bad data.
4. Transmit configuration and control information to the FC via UART 1.
5. Associate a sensor datum with each position datum (data streams are not synchronized) and write the data record to fixed disk.
6. Perform translation, rotation, and scaling of each new data record, update graphics display with the data.
7. Recognize and interpret keyboard input, modify survey parameters as commanded.

The BC software performs these tasks in real-time; this is illustrated by considering the following sequence of events. During a survey, a new data packet arrives at UART 2 from the AP-L1 while the software is writing an older data record to the fixed disk. Fixed disk activities are immediately suspended and the code which services UART 2 is activated to receive the data packet. This task switch is accomplished in less than 50 msec; otherwise, the incoming data will be corrupted. After the data packet has been safely received, the fixed disk software resumes writing the original information without confusion. Each internal task has the capacity to be interrupted, and then to later resume without loss of data. Reception of the two data-streams from UART 1 and UART 2 take highest priority. The software is able to receive data in interleaved fashion when data arrives simultaneously at each port. For these reasons, the BC software cannot use the normal system (DOS or BIOS) facilities to interface with the keyboard, serial ports, or

fixed disk. Alternate facilities have been coded which are able to function in the GAUSS real-time environment.

The BC software was written in C using a commercial real-time multitasking kernel, RTKernel. RTKernel allows each of the seven software tasks to be run as an independent program within the BC. Each program is interrupt driven and can be assigned a priority which is used in allocation of CPU time. Using the multitasking kernel, fully functional real-time GAUSS base station software requires only 31 kilobytes of source code.

GAUSS provides a real-time map of a survey using a video graphics display. The map is used to monitor the trajectory of the survey vehicle and to view the geophysical data. Map color at each location is determined by the value of the field data corresponding to that point. This approach is sensible since the information for each new incoming datum can be displayed independently of all other data. As seen in Figure 3, this technique is effective when the geophysical data has a restricted dynamic range. This data was taken by GAUSS using the total field magnetometer over a buried vertical steel pipe. The full colorscale of the display can be applied to delineating the target.

Difficulties arise if the geophysical data has a wide dynamic range. Figure 4 shows a possible scenario in which a magnetic survey is performed for the purpose of locating buried drums. A metal building is located near the survey site and produces a substantial gradient in the magnetic field. We wish to produce a color map from this data using five colors. Even though the presence of the drums is clearly indicated by the data, we cannot assign color levels (without *a priori* knowledge) so that all drums are detected on a map. If we assign a uniform color scale as indicated by the horizontal lines on the chart, none of the drum anomalies will be displayed on the map.

One alternative is to increase the number of colors available for the graphics display. This is impractical because the human eye can distinguish only a limited number of shades. Another solution is to use a real-time filter which removes data having undesirable wavelengths. For the situation of Figure 4, the long wavelength anomaly of the building is removed, leaving the short wavelength drum anomalies. The full dynamic range of the color display can then be applied to the drum anomalies. We have written software to efficiently perform spatial filtering of randomly spaced data points. GAUSS survey data has been post-processed using the software providing excellent results. We will include the filter algorithms in the GAUSS prototype.

This approach incurs computational overhead because the color to be displayed now depends on the value of other data. The computational requirement is further increased because the GAUSS data coordinates are random. In the prototype, an auxiliary processor with monitor will perform filter computations and display geophysical data. The original BC will provide a display of the survey trajectory to guide the vehicle remote pilot in conducting a complete survey.

Figure 4. Illustration of difficulty in assigning color levels for data having a large dynamic range.

2.2 Sensor Systems

The pre-prototype sensors are a total field magnetometer and an induction electromagnetic sensor. We have selected these techniques because they are complimentary and widely applicable for environmental site characterization. The magnetometer can detect ferrous objects at relatively long ranges. For example, total field magnetometers are capable of detecting an oil drum buried at 30 ft. GAUSS uses this long range capability for rapid reconnaissance sweeps of large areas. Targets that can be detected include UXO, subsurface drums, pipes, reinforced concrete, and landfills containing ferrous material.

The electromagnetic induction sensor can also detect ferrous objects, generally at a shorter detection range, but can also detect nonferrous metallic objects as well as environmental conditions having discontinuous conductivity. Example applications of the EM instrument are: detection of edges of filled pits or trenches; mapping of chemical leach fields; locating shallow subsurface voids or structures; shallow water marine bathymetry; and detection of conductive subsurface objects.

Commercial sensors do not exist which can meet the size, weight, power consumption, and performance requirements of GAUSS. Geophex has produced a custom total field magnetometer and a custom induction sensor for use in GAUSS. We have presently packaged these instruments for hand-held use with the pre-prototype, but they are designed to be used with the ROH. Design considerations and performance characteristics of these sensors will be discussed.

2.2.1 Magnetometer

The total field magnetometer is appropriate for low altitude airborne application since it provides stable output readings irrespective of orientation. Also, the total field instrument can detect ferrous objects at a range greater than a magnetic radiometer. The two types of commercially available total field magnetometers are the nuclear precession magnetometer and the optical pump magnetometer. The nuclear precession magnetometer is unsuited for GAUSS application due to its relatively slow update rate and due to instrument weight. Optical pump magnetometers, such as rubidium or cesium vapor instruments, provide highly accurate readings at suitable update rates (> 5 per second) but are also unsuitably heavy (≈ 20 lb for a representative commercial cesium vapor unit).

Geophex has constructed a lightweight, total field magnetometer using a commercial, three axis fluxgate magnetometer, the Bartington Instruments model MAG03MCL. Function of the total field magnetometer is illustrated by the basic block diagram of Figure 5. The fluxgate magnetometer provides three field-voltages, V_x , V_y , V_z , each proportional to the component of the magnetic field aligned with the respective fluxgate axis. The field-voltages are buffered and filtered by three-channel analog circuitry. Low-pass filtering is used to remove the strong 15.625 kHz voltage component present in each signal due to the fluxgate excitation oscillator.

The filtered field-voltages are sampled and digitized simultaneously by a bank of AD7703 20-bit, sigma-delta, analog to digital (A/D) converters. The A/D converters are controlled by a CMOS computer, model 5FLCD manufactured by Onset Computer Corporation. The computer has been modified to operate with an external 4.9152 MHz clock circuit which also drives the A/D converters. Use of a common clock allows the converters to be synchronized with each other and the computer. We have found that this synchronization significantly reduces the influence of on-board electrical interference. The CMOS computer communicates with a radio transceiver using an RS-232 port.

Power conditioning circuits provide isolated power for the digital circuits, analog circuits and the fluxgate sensor. The total field magnetometer shares a single battery with other devices without interference, a requirement for GAUSS since all electronic devices on the survey platform must use a single common battery.

The computer runs a 14.5 kilobyte control program residing in on-board non-volatile memory. The control program, written at Geophex, consists mainly of assembly-level drivers and interface routines to control the A/D converters. Higher level functions are performed by floating point tokenized BASIC routines. Duties of the computer include synchronization, initialization, and periodic recalibration of the A/D converters, reading and formatting of A/D data, computation of field magnitude, and communication with the BC.

Figure 5. A basic block diagram of the GAUSS total field fluxgate magnetometer.

The computer determines field magnitude using a real-time transformation of the raw field-voltage data. The manufacturer guarantees fluxgate alignment to be orthogonal within $\pm 0.5^\circ$ per axis. This slight misalignment results in considerable heading error if Pythagorean's theorem is used to calculate field magnitude using raw fluxgate data. As seen in Figure 6, the uncorrected heading error exceeded 240 nT.

The data transformation can be described in terms of a general vector transformation $\mathbf{B} = \mathbf{B}_0 + \bar{\mathbf{T}}\mathbf{B}'$, where:

$$\mathbf{B}' = \begin{bmatrix} B'_x \\ B'_y \\ B'_z \end{bmatrix} = \text{raw fluxgate field vector}, \quad \mathbf{B}_0 = \begin{bmatrix} B_{x0} \\ B_{y0} \\ B_{z0} \end{bmatrix} = \text{field offset vector},$$

$$\mathbf{B} = \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} = \text{true field vector}, \quad \bar{\mathbf{T}} = \begin{bmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{bmatrix} = \text{transform tensor}.$$

$|\mathbf{B}|$ can be expressed in terms of $\mathbf{B}'$ and the transformation constants $\mathbf{B}_0$ and $\bar{\mathbf{T}}$,
 $|\mathbf{B}| = C_0 B_x^2 + C_1 B_y^2 + C_2 B_z^2 + C_3 B_x B_y + C_4 B_y B_z + C_5 B_z B_x + C_6 B_x + C_7 B_y + C_8 B_z + C_9,$

where the coefficients C_k are functions of the elements B_{i0} and t_{ij} . The coefficients are determined during a magnetometer alignment procedure in which $\mathbf{B}'$ data is recorded for multiple sensor orientations while in a constant magnetic field. The coefficients are then numerically found by applying the downhill simplex method to the data. Once the polynomial coefficients are determined, they are coded into the magnetometer software. The polynomial transformation substantially reduces heading error as indicated in Figure 6.

Figure 6. $|B|$ calculated using fluxgate data and using corrected data.

Advantages of the fluxgate total field magnetometer over conventional total field magnetometers are its light weight and high update rate. The primary disadvantage is that the readings can drift with temperature due to the thermal properties of fluxgate cores. During six months of use, the magnitude of drift that we have experienced has been too small to effect our surveys. Properties of the total field fluxgate magnetometer are listed in Table 1.

Table 1. Specifications of the GAUSS fluxgate total field magnetometer.

thermal drift	< 1.5 nT/°C in 50,000 nT field
weight (all electronics & sensor)	9.5 oz
update rate (raw vector data)	1024 sec ⁻¹ max.
update rate (corrected total field)	30.7 sec ⁻¹ max.
resolution	< 0.5 nT
heading error (worst case)	< 7 nT

2.2.2 Electromagnetic Induction Instrument

Geophex has been involved with EM instrument research for more than 10 years. We have redesigned our state-of-the-art EM instrument electronic systems for use with the ROH. During this redesign we were able to make several improvements in instrument performance. The areas that we addressed to create a ROH-capable instrument were:

1. Replace discrete logic with PALs when possible.
2. Reduce circuit complexity by performing more functions with CPU.
3. Replace hand-wired protoboards with printed circuit boards to improve reliability.
4. Modify system to operate from a unipolar voltage supply.
5. Reduce system baseline drift.
6. Allow software selectable waveform generation.

These goals were successfully completed resulting in an EM electronics assembly using a single 3.5 in by 8.5 in printed circuit board, and weighing less than 12 ounces. By comparison, the previous design required three circuit boards, heavy, unreliable interboard connections, and three separate battery stacks. Geophex is cooperating with an outside company who is developing a surface-mount version of the new EM electronics system. This version will have additional size and weight savings and improved ruggedness. Prototypes are expected during the Spring of 1995.

A basic block diagram of the GAUSS electromagnetic (EM) induction sensor system is shown in Figure 7. The system is comprised of electronics and a coil assembly. Electronic systems are controlled by a proprietary high performance computer based on the Motorola 56001 digital signal processing (DSP) chip. During operation, a synthesized voltage waveform is applied to the transmit (Tx) coil. The Tx-coil current produces a strong primary electromagnetic field. If a conductive object is in the vicinity, this primary field will induce electric current in that object. The induced current gives rise to secondary electromagnetic fields which, in turn, generate potential across the receive (Rx) coil. Changes in Rx coil voltage are detected and indicate changes in conductivity of the surroundings. The Rx coil signal is of small magnitude and is processed by precision, low noise analog circuitry which supplies appropriate filtering and a gain exceeding 1500. The receiver is broad-band allowing multifrequency operation.

Since the instrument is battery powered, transmit field strength will decrease during use due to battery voltage decay. A reference coil (Px) is located to monitor the Tx coil field

strength. The Rx/Px signal ratio is not effected by Tx signal strength, so this ratio is used for target detection.

Figure 7. A simplified block diagram of the GAUSS electromagnetic sensor system.

The Tx voltage waveform is synthesized using a pulse width modulation (PWM) scheme. The computer produces a bitstream which controls a tri-state bridge circuit. The bridge modulates the transmit supply voltage and produces a PWM voltage waveform. The advantage of this transmitter is that the computer bitstream is easily modified to produce any desired waveform, resulting in multi-frequency operation. Lower frequencies are able to penetrate deeper into the Earth while higher frequencies are useful to detect shallower objects. A single operating frequency is presently used, the frequency is user selectable in the range of $400 \text{ Hz} < f < 1200 \text{ Hz}$.

After analog processing, the Rx and Px signals are digitized by a Crystal CS5336 stereo A/D converter at 36.45 kbps per channel. The DSP computer then cross correlates each digitized waveforms with a recorded version of the Tx waveform. This process provides both amplitude and phase information for target anomalies while decreasing noise bandwidth by a factor of 3200. Software for the DSP computer is written primarily in assembly language since very tight timing requirements are in effect. The computer must maintain synchronization while simultaneously transmitting a control sequence to the Tx coil driver, controlling and reading the A/D converter, and performing signal processing on the Rx and Px channel data. Additionally, the EM system sensing circuits must be inactive during radio transmission of the telemetry system to avoid interference.

Traditionally, the Rx and Tx coils are widely separated in EM systems, this is termed as the bistatic configuration. Separation of the coils prevents the strong Tx field from obliterating the weak secondary field at the Rx coil. A long boom is used to support and

align the separated coils. The bistatic configuration results in a large, heavy instrument. Geophex has constructed and tested initial prototypes of a compact monostatic coil arrangement as depicted in Figure 8.

Figure 8. The GAUSS EM instrument prototype monostatic coil assembly.

The monostatic configuration utilizes two transmit coils, Tx1 and Tx2. The transmit coils produce magnetic fields of opposite polarity. The transmit coils are designed so that when connected in series, the net magnetic flux vanishes over the area of the Rx coil. The need for wide coil separation is alleviated since the Tx field has little influence of the Rx signal. The resulting EM sensor is considerably lighter and more compact since a supporting boom is not needed.

2.2.3 Remotely Operated Helicopter (ROH)

Geophex maintains and flies three remotely operated model helicopters which were assembled from commercial kits and then configured by Geophex personnel. Although our Phase I research does not directly involve use of a ROH platform, we have used them to study technical issues associated with Phase II and to provide flight training in preparation for the airborne prototype. A test flight is shown in Figure 9.

Our largest ROH is a Schoonard X-CELL 60 series custom helicopter manufactured by Miniature Aircraft USA. This helicopter is capable of lifting a maximum payload of 15 pounds and has routinely been used by others to carry an 8 pound cam-corder for 25 minute sorties. The GAUSS sensor package is anticipated to weigh 5 pounds which permits larger fuel capacity and longer sorties. It is anticipated that the ROH will fly at an altitude between one and two meters at speeds less than 10 mph.

The ROH construction material is mostly aluminum and stainless steel with wooden rotor blades. Some ferrous material is used which results in a 50 nT anomaly when detected at 2 ft by the GAUSS magnetometer. It is expected that the conductive material of the helicopter will also produce a substantial anomaly in the EM instrument readings. We will rigidly fix the position of the sensors with respect to the ROH so that the anomaly caused by the helicopter will result in a fixed shift in the instrument baseline readings. The spatial variations in the target anomalies will not be influenced by the constant offset due to the ROH. This technique is commonly used in sensor instrumentation construction and in full-scale airborne geophysical surveys.

Figure 9. Test flight of ROH with payload.

3.0 Test and Evaluation

During construction, the pre-prototype subsystems were constructed, configured and tested thoroughly on an individual basis. Modifications were made until subsystem performance was acceptable for system integration. Rudimentary BC software was written, then functionality and subsystems were gradually added. We continued testing after full system configuration was attained to improve performance and to determine the applicability of the pre-prototype to ROH surveys. This section provides information regarding how the GAUSS pre-prototype is used, typical test surveys, and survey results.

3.1 Logistics

The GAUSS pre-prototype is presently a productive tool that can be used by two field technicians to perform rapid, nonintrusive site investigations. This section explains how the pre-prototype is used to perform a site characterization. Figure 10 shows the GAUSS components in the field, ready for use. The BC (inside the van), communicates with the AP-L1 laser position measurement system and with a spread-spectrum RF modem (antenna is visible above the door post). The total field magnetometer (left side of van door) communicates with the BC using a hip-pack radio modem. The hip-pack, located at the foot of the magnetometer, is not clearly visible in this photograph. The cylindrical optical target mounted on top of the magnetometer is used by the POS. The EM instrument (right side of van door) electronics are mounted at the mid-point of the sensor boom. The RF modem and communications optical isolator are affixed below the sensor electronics. A nonconductive optical target is mounted on the underside of the boom.

Two technicians are required to perform a site characterization. Technician-1 (T1) operates a sensor, technician-2 (T2) operates the BC and directs the survey. T1 will be replaced by ROH and pilot in the Phase II prototype. To start a survey, a sensor is selected (magnetic or electromagnetic), the sensor is powered, and sensor software is initiated. Both radio transceivers and the AP-L1 are powered and configured. T1 carries the sensor into the field of view of the AP-L1 which is adjusted by T2 to lock onto the optical target. T2 starts the GAUSS BC software which prompts the users to set up the survey.

T2 is prompted to enter data pertaining to sensor sensitivity. T1 is directed to occupy two locations which define a survey baseline, and a third which defines the depth of the survey area (normal to the baseline). These positions are recorded by the software and used to draw a survey area outline and grid as seen in Figure 11. The boundary and grid serve as landmarks which help T2 direct the path of T1. The actual survey is not constrained to stay within the indicated area.

The survey is now underway. T1 walks across the site with the objective of adequately covering the area as depicted in Figure 12. As T1 walks, geophysical and positional data are automatically measured, recorded, and displayed at a rate of 2 sets per second. If T1 remains stationary, data recording is suspended until T1 moves to a new location. During the survey, T2 can view survey trajectory or geophysical data on the graphics

display and adjust parameters of the display. T2 uses display information to direct T1 to locations of interest or areas requiring coverage. A warning indicator alerts T2 if T1 has moved beyond the survey boundary. An audio indicator provides T2 with the tracking status of the AP-L1. If the system loses lock with the optical target, T2 requests that T1 remain close to the location where lock was lost. The AP-L1 will then automatically search and reacquire the optical target. The survey is concluded using a keyboard command. During the survey northing, easting, altitude, and geophysical data are recorded. This information is available for post-mission processing and survey documentation.

Figure 10. Components of the GAUSS pre-prototype.

3.2 Geopex Geophysical Test Site

In November 1994, Geopex constructed a 1/4 acre geophysical test site. The site features targets buried at known depths and orientations which allows test results to be interpreted objectively. Since its construction, this site has been the location for most GAUSS test surveys. GAUSS has been used in site construction. This site had previously been used for industrial purposes and therefore, contains many extraneous targets. Many objects have been located using GAUSS, then excavated. Clean up of the remaining objects continues. This section describes the test site and presents the results of GAUSS magnetic and electromagnetic surveys of the site.

Figure 11. Screen dump of a trajectory map from a GAUSS electromagnetic survey.

Figure 12. A GAUSS electromagnetic survey in progress.

Figure 13 shows the location of the subsurface targets. The site presents a challenging, realistic location for geophysical sensing. Chain link fences border the east and west sides of the site and metal buildings are located near three borders. These objects influence the sensors which are designed to detect ferrous objects or conductors.

Details of the subsurface targets are provided in Figure 14. The storm drain system uses two ft diameter reinforced concrete pipe for the north-south leg. The center of the pipe is approximately 4.5 ft deep. The east-west leg uses two types of pipe. West of the vault, one ft diameter ceramic pipe is buried at a depth of 3.5 ft. East of the vault, one ft diameter reinforced concrete pipe is located at a center depth of 4 ft.

Figure 15 is a display of total field magnetic data collected from the test site during a GAUSS survey. The data was processed using GAUSS filter programs to remove long wavelength anomalies, then gridded and contoured using a commercial software package. Two technicians conducted the survey, expending 25 minutes of effort and collecting 2274 data points. The locations of ferrous targets are indicated by dark outlines. Note that the vertically oriented targets produce a monopolar (bullseye) anomaly, while horizontally aligned targets produce a bipolar anomaly. The incidental anomalies are due to objects which have not yet been excavated.

Figure 13. Location of subsurface targets at the Geophex Geophysical Test Site in Raleigh, NC.

- 1 3 each 10.5"x30" aluminium plates; 0.5 mm thick

- 2 55-gal steel drum, dirt-filled, buried sideways

- 3 Shallow trench filled with rocks (6' long)

- 4 6.5"x5' PVC pipe (Geophex Time Capsule)

- 5 6.5"x51" galvanized steel pipe dirt-filled (buried upright)

- 6 6.5"x6' galvanized steel pipe dirt-filled (buried sideways)

- 7 4"x5' aluminium pipe

- 8 55-gal steel drum, dirt-filled, buried upright

Figure 14. Description of the targets buried at the Geophex Geophysical Test Site

A manual survey was performed over a 70 ft by 60 ft area for comparison. Position was determined manually by marking a square grid on the ground. Two technicians, using measuring tapes and spray paint, constructed a regular 2.5 ft grid, then magnetometer data was collected at the grid intersection points. The two technicians expended 195 minutes of effort and collected 725 data points. The GAUSS magnetic survey was more efficient than the manual survey by a factor of 24.

Figure 15. Data from GAUSS magnetic survey at Test Site, locations of known ferrous targets are indicated.

Data from a GAUSS electromagnetic survey of the Test Site are shown in Figure 16. During the survey, we configured the electromagnetic sensor to operate at a single frequency, 7290 Hz, and collected 1895 data points in less than 18 minutes. GAUSS filter software was then used to remove short wavelength anomalies from the data. The data shows that the reinforced concrete pipes were detected, the unreinforced ceramic pipe was not. Even though the small amount of steel in the reinforcing mesh could not be detected in magnetic surveys, the conductive nature of the mesh was detected by the electromagnetic instrument.

The strong contour lines at the south edge of the survey are caused by the warehouse building which is 16 ft high and has metal siding. The shed on the east side of the site has a metal roof with open sides, and produced a much smaller anomaly.

Figure 16. Filtered 7290 Hz in-phase electromagnetic data from a GAUSS survey showing detection of storm sewer system.

3.3 Diabase Dike Detection

In December 1994, we used GAUSS for the successful completion of a geophysical survey. The survey objective was to detect and characterize any diabase dikes located on the site. Diabase dikes are subsurface, intrusive, igneous formations which contain magnetite and are thus detectable using a magnetometer.

We conducted reconnaissance surveys along five profile lines to detect the presence of diabase dikes. The GAUSS magnetometer and remote radio transmitter were operated in manual trigger mode. Base station software, running on a laptop computer, was configured in line-survey mode. Data were collected, and broadcast, by the magnetometer at 20 ft. intervals along each profile line. No difficulty was encountered with radio transmission through heavy brush and timber at ranges up to 1/3 mile. The information was received and displayed in real time by the base station. At the completion of each survey line, we were able to locate dikes by inspecting the GAUSS graphical display. GAUSS profile data is superimposed along each profile line in Figure 17.

After we located the intersections of the dikes with the reconnaissance lines, we operated the GAUSS magnetometer in independent mode to trace the location of the dikes between the lines. Finally, the magnetometer was used to conduct high sample density attitude surveys along lines transverse to each dike. The attitude survey data was used to determine dike depth, dike width, and tilt-angle of each dike wall. We found GAUSS to be a very efficient tool for completion of this project and plan to use the GAUSS pre-prototype on additional environmental and geophysical jobs during the spring of 1995.

Figure 17. Site map showing diabase dikes located by GAUSS, reconnaissance data is plotted using dotted lines.

4.0 Conclusions

Geophysical surveys of environmental sites provide a nonintrusive means of evaluating subsurface conditions, yet for many sites, conditions are sufficiently hazardous that personnel cannot enter the site, or elaborate personal protective equipment may be required. Rapid, digital geophysical surveys are needed for these dangerous sites, but the problem is compounded by a need for sensors to be close to the ground surface for accurate detection and analysis of small features. A geophysical surveying and analysis system is needed that is cost-effective, accurate, nonintrusive, and promotes personnel safety.

During Phase I research, Geophex has designed and built an automated data acquisition and processing system. We have also constructed and tested lightweight magnetic and electromagnetic sensors. Performance of all subsystems was verified by stand-alone testing. We integrated the DAP system and sensors to create a hand-held automated survey system. We then tested the hand-held system to determine the applicability of the technology to a ROH based remote survey system. Results of our tests are as follows:

- We determined that the tracking system was capable of automatically tracking a sensor-carrying survey vehicle as it moves in a random path. We were able to record positional data while tracking. The system was able to reacquire the survey vehicle when loss of lock occurred.
- We determined that the DAP can simultaneously collect, record, and graphically display data from a geophysical instrument and from the tracking system while the survey vehicle is in random motion. Data was processed at a rate of 7200 points per hour.
- We determined that the geophysical sensors can acquire useful data when carried by a moving vehicle. These data were used to detect and locate subsurface targets. During these tests GAUSS was observed to be more efficient than alternate survey methods.
- We determined that an auxiliary processor is necessary to provide a meaningful real-time graphics display of geophysical data. The feasibility of this was demonstrated by writing filter software and studying the program execution time while post-processing data.

Assessing subsurface conditions is an important component of soil and groundwater environmental assessment and remediation programs. GAUSS provides a tool for assessing these subsurface conditions faster, better, cheaper, and safer than is possible with current technology. The key environmental objectives this program addresses are reducing assessment costs, reducing assessment time, increasing safety, and enhancing the information that can be gained nonintrusively.

5.0 Recommendations

Production of an ROH-based survey system poses many logistical problems. However, results of the Phase I research indicate that there are no technical barriers to producing a successful system. We have demonstrated the ability to track and record geophysical data from a moving platform. This data has been used to locate subsurface targets. Our sensor, telemetry, and power systems have been designed so that they can be modified for airborne application and are well within the ROH weight budget. The ROH is a proven technology for payload bearing applications. Piloting of the ROH requires some expertise, but maintaining steady low-level flight is not difficult.

The ability of the ROH survey platform to operate over difficult terrain or dangerous conditions provides many potential applications for the system. GAUSS, when completed under this project, should have a variety of environmental applications at DOE's nuclear, biological, and chemical (NBC) waste sites as well as ordnance and explosive waste (OEW) sites. A matured GAUSS should also find its applications in battlefields for locating and neutralizing buried mines on land, beach, and surf zone. The low cost of this system and high data acquisition rates make it a viable alternative to present technologies.

The ROH and DAP system are flexible enough to accept a wide range of payloads. For example, with software modifications, a digital camera can be flown in lieu of geophysical instruments. The present telemetry system can download one 512 pixel by 400 pixel by 64 color image every 80 seconds. Wider bandwidth radios can be used if higher frame rates are required, analog transmission can be used if real-time video is desired. These images can be position stamped by the POS.

Based on the results of our Phase I research, and the potential of the ROH survey system, we recommend that research proceed to develop an airborne prototype. We feel that Geophex is eminently qualified to capitalize on the advances made during the first phase research. The capability of the prototype to survey hazardous locations should be evaluated.

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