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THREE-DIMENSIONAL SUBSURFACE IMAGING SYNTHETIC APERTURE RADAR

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DISCLAIMER

2.6 Three-Dimensional, Subsurface Imaging Synthetic Aperture Radar

CONTRACT INFORMATION

Contract Number	DE-AR21-93MC30357
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Period of Performance	September 20, 1993 to March 20, 1995

FY95 Program Schedule

	S	O	N	D	J	F	M	A	M	J	J	A
Hardware/Software Integration	—	—										
Radar Calibration		—										
Data Collection Experiments			—									
Demonstration & Evaluation				—								
Final Report Submission					▽							
Contract Completion							▽					

OBJECTIVES

The objective of this applied research and development project is to develop a system known as "3-D SISAR". This system consists of a ground penetrating radar with software algorithms designed for the detection, location, and identification of buried objects in the underground hazardous waste environments found at DOE storage sites. Three-dimensional maps of the object locations will be produced which can assist the development of remediation strategies and the characterization of the digface during remediation operations. It is expected that the 3-D SISAR will also prove useful for monitoring hydrocarbon-based contaminant migration after remediation.

BACKGROUND INFORMATION

Mirage Systems is a leader in the development of compact, low cost, HF/VHF/UHF instrumentation radars for unique applications. Since 1989, Mirage's efforts have led to radar development contracts with the DOE, ARPA, EPRI, and the US Navy, Army, and Air Force.

Mirage Systems has designed and equipped a 22-foot long specially configured trailer, called the Mobile Test Vehicle (MTV), as a sensor system test platform. The MTV is being used as a mobile laboratory to house the 3-D SISAR in support of field demonstrations of this underground imaging technology.

PROJECT DESCRIPTION

Approach

The underground imaging technique being developed under this contract utilizes a spotlight mode Synthetic Aperture Radar (SAR) approach which, due to its inherent stand-off capability, will permit the rapid survey of a site and achieve a high degree of productivity over large areas. When deployed from an airborne platform, the stand-off technique is also seen as a way to overcome practical survey limitations encountered at vegetated sites. Figure 1 illustrates the technique and data collection geometry that will be used for the test and evaluation of the concept.

In a spotlight mode SAR, the area to be surveyed is "spotlighted" or "stared at" as the radar path forms the synthetic aperture, typically a circle. When compared to SAR strip mapping, the spot-light mode enhances spatial resolution and increases the energy used to illuminate the ground.

The technique provides high coherent integration gain which, when combined with the inherent sensitivity of the frequency modulated, continuous wave (FMCW) signal transmission method, allows a significant improvement in imaging quality. These features are very beneficial for subsurface characterization since 1) long wavelengths, which typically produce images with limited spatial resolution, are needed to penetrate the ground, and 2) the subsurface has inherently high propagation losses requiring more available energy for effective ground penetration. The ultra-wide bandwidth of the FMCW signal provides for improved resolution in the depth dimension as well.

Two different imaging techniques are being applied to the collected data. A Mirage-developed matched filtering technique will be applied to the data in order to detect, identify, and locate objects based on their a priori scattering characteristics. Tomographic processing techniques will also be used to extract high resolution, three-dimensional images of the subsurface from the radar data.

Overview of Tasks

A matched filter image processing algorithm has been developed for the detection and identification of buried objects. Scattering models for several types of buried objects (test spheres, barrels, barrel lids, and pipes) have been constructed from electromagnetics modeling programs for use with the matched filter algorithm.

A new radar is being developed that produces the high quality data required by the image processing algorithms. After the radar is assembled, there will be a series of tests to collect data on actual underground objects, followed by a field demonstration to evaluate the performance of the imaging algorithms in a controlled environment.

Preceding the software and hardware development, a series of systems engineering tasks were performed to estimate the radar requirements, specify the desired performance, and produce a plan for the field tests and a series of data collection experiments that will assist the algorithm development.

Underground Imaging Approach Using Matched Filtering

The goal of the 3-D SISAR development is to produce a three-dimensional presentation of the near-surface underground environment that can be applied to the determination of the presence and extent of buried waste. The approach taken by Mirage for this research and development project is one that produces a representation of buried waste containers based on the unique characteristics of the scattering of electromagnetic waves. This approach has the benefit that it searches for a set of unique priorities of the radar returns that characterize the shape, dimensions, and orientation of a given buried object. Once an object is located and identified, the imaging software draws a representation of that object in a three-dimensional space that defines the underground mapped region. Figure 2 is a display of the matched filter output for a barrel buried at a depth of 4 meters. The middle slice of data clearly shows the correlation peak produced by the barrel at the correct coordinates.

There are many facets to producing underground images using GPR. One of the major advantages of the matched filter approach is that it overcomes a basic difficulty with other techniques that attempt to image the underground environment directly. This difficulty results from the fact that the wavelengths used for underground imaging are on the order of the linear dimensions of the object.

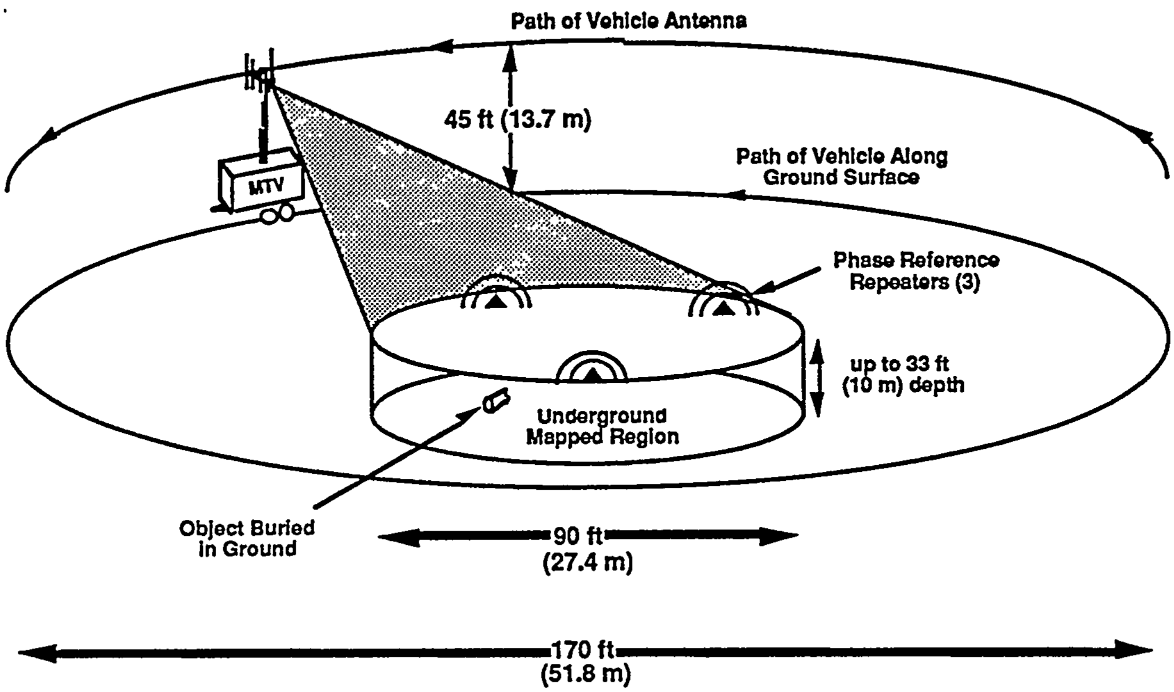

Figure 1. Site geometry for project test and evaluation.

The scattering produced by such objects is in the Rayleigh regime, not the optical regime where one normally sees an image that resembles the object in shape and size. In other words, the intensity information alone from the radar return does not clearly distinguish object size and shape because the wavelengths are too long to provide much detail. More traditional techniques attempt to image the entire underground environment.

The technique determines the best correlation between the measured radar data and a set of potential matching functions, with each function representing an anticipated object-subsurface model. After an object is located and identified, the display program draws a representation of it at the location and depth on a 3-D display.

An advantage the customized matched filter may have over other imaging algorithms is that its performance can be greatly enhanced if the type (or characteristics) of an object is known apriori. An additional advantage is that it avoids the numerical and convergence concerns of other techniques (e.g., iterative approaches). However, its performance robustness to complex underground object configurations is unknown and will be explored during the test and evaluation task.

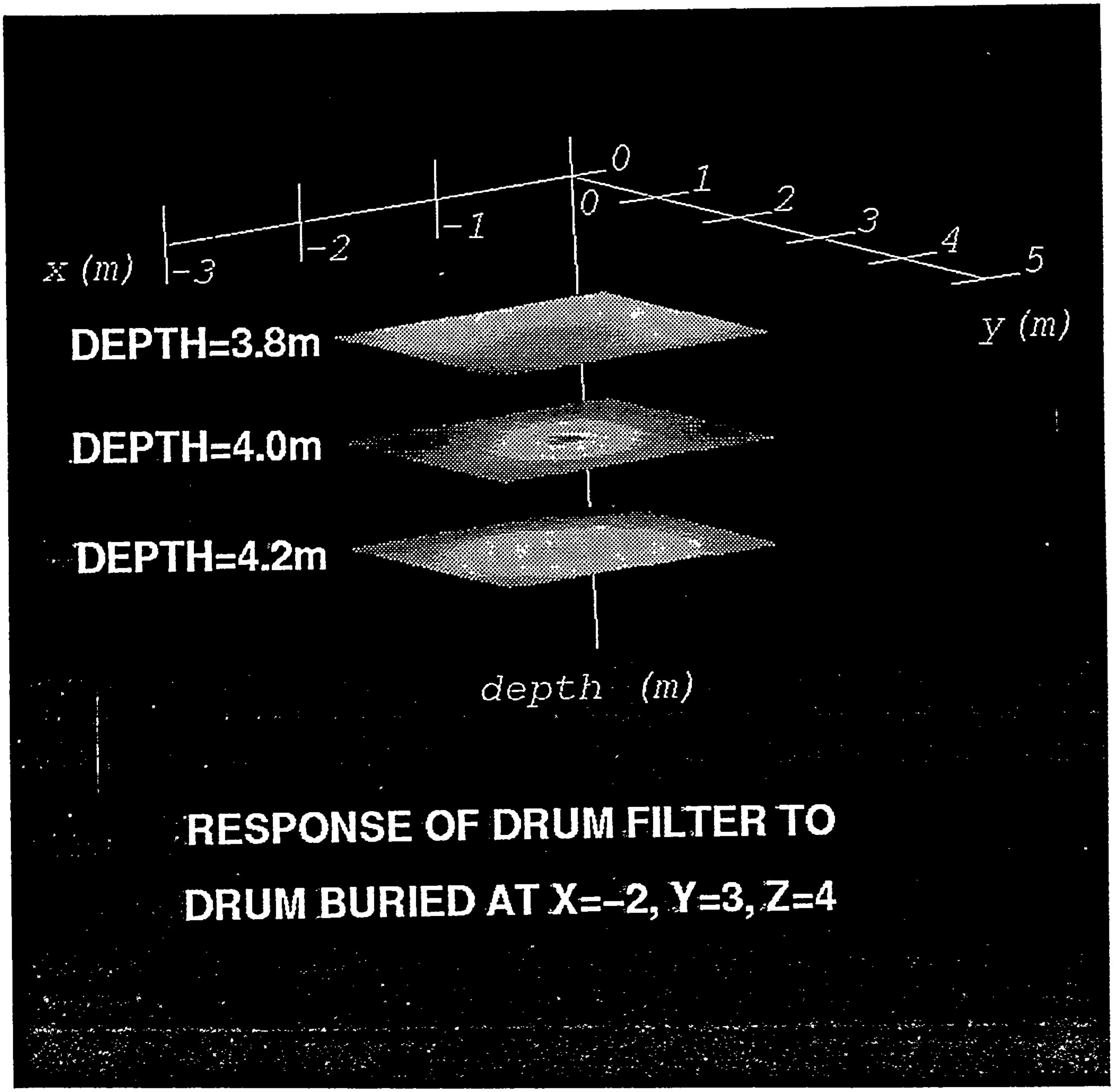

Figure 2. Matched Filter output for a buried barrel

Alternate Imaging Algorithm Approaches

Mirage recognizes that effective imaging is key to a successful 3-D SISAR system. Mirage has provided the framework for successful imaging by including flexible spatial and frequency diversity in its data acquisition scheme. Because of the complexities of the underground environment, the collective imaging expertise and algorithms developed by the University of Kansas and SRI International are also being applied to this project. These algorithms were developed for related applications, so adapting them to the 3-D SISAR application is straightforward. The subcontractor tasks are primarily focused on the incorporation of the Mirage spotlight mode data acquisition scheme, the radar waveform parameters, and propagation effects of the underground environment. An approach combining several techniques offers advantages in presenting a more complete picture of the underground environment. Figure 3 illustrates how these algorithms will be integrated into the image processing flow.

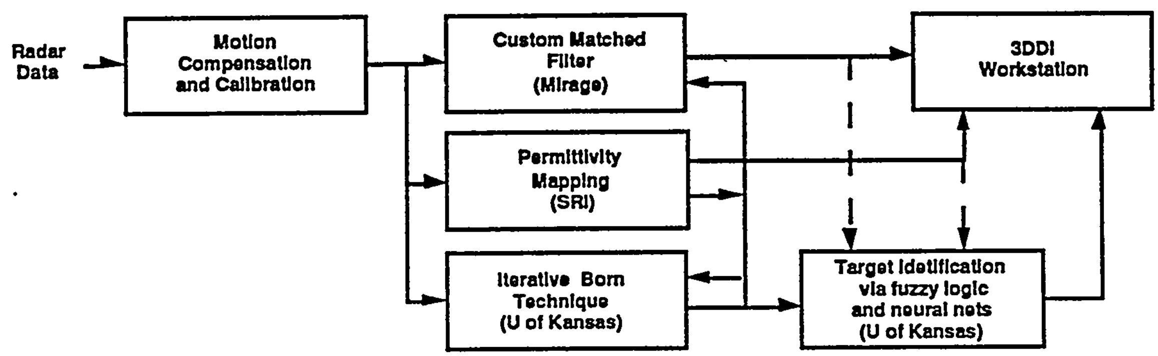

Figure 3. Integration of imaging algorithms

The approaches used by the University of Kansas and SRI International are quite different than the approach used by Mirage for the matched filtering process. The Mirage approach relies upon the correlation of the amplitude and phase of the scattered radar energy of the objects with models of the predicted behavior of the objects in order to identify the objects. The approach by the University of Kansas employs a finite difference, time-domain algorithm for imaging coupled with a neural network to identify objects. SRI International is developing a tomographic imaging algorithm which also provides an estimate of the subsurface permittivity from measured radar data. The resulting estimate can be used to improve the performance of each of the imaging algorithms.

Radar Development

Mirage has developed a small, lightweight radar to provide high quality data for the underground imaging algorithms. The radar is housed in a mast-mounted enclosure, with major components arranged in a compact, easy to assemble and repair layout. In function, this unit is the equivalent of nearly a full rack of equipment, mostly contained in three major subassemblies. The unit is sealed from the environment, and uses an air-to-air heat exchanger so that dirt and moisture do not enter the electronics portion of the unit.

As shown in Figure 4, the antenna and radar subassembly are located at the top of a pneumatic mast attached to the Mirage Test Vehicle, and are elevated to a height suitable for standoff operation, about 40 feet above ground. This configuration will be used for the field experiments and demonstrations. The radar signal data is sent down the mast via a high speed digital link to a controller and a data collection subsystem located in the trailer. Figure 5 is a simplified block diagram of the radar and data collection subsystem. Important features of this design include provisions for adequate performance monitoring and fault isolation, and ruggedness of design to withstand the rigors of field use.

Antenna Subsystem The antenna is a split boom log-periodic antenna, chosen for a narrow pattern in the horizontal plane, about 70 degrees. This is critical from an imaging standpoint because radar energy that is not directed to the imaged volume will still be reflected from the surrounding ground and surface objects, producing additional clutter returns that can obscure the signal returns from objects buried within the desired imaging volume. The antenna being procured has a radiation pattern that optimally illuminates the underground imaging volume, and has the extended low frequency coverage required for the system.

Data Acquisition Subsystem The function of this subsystem is to control the radar operation and provide a means to display, collect, and archive the radar data. It consists of a VME-based subsystem using a Force Computers 5CE processor module running a real-time multi-tasking environment, two hard drives for storing program and radar data, a tape drive for archiving radar data files, and interfaces to the radar and calibration equipment.

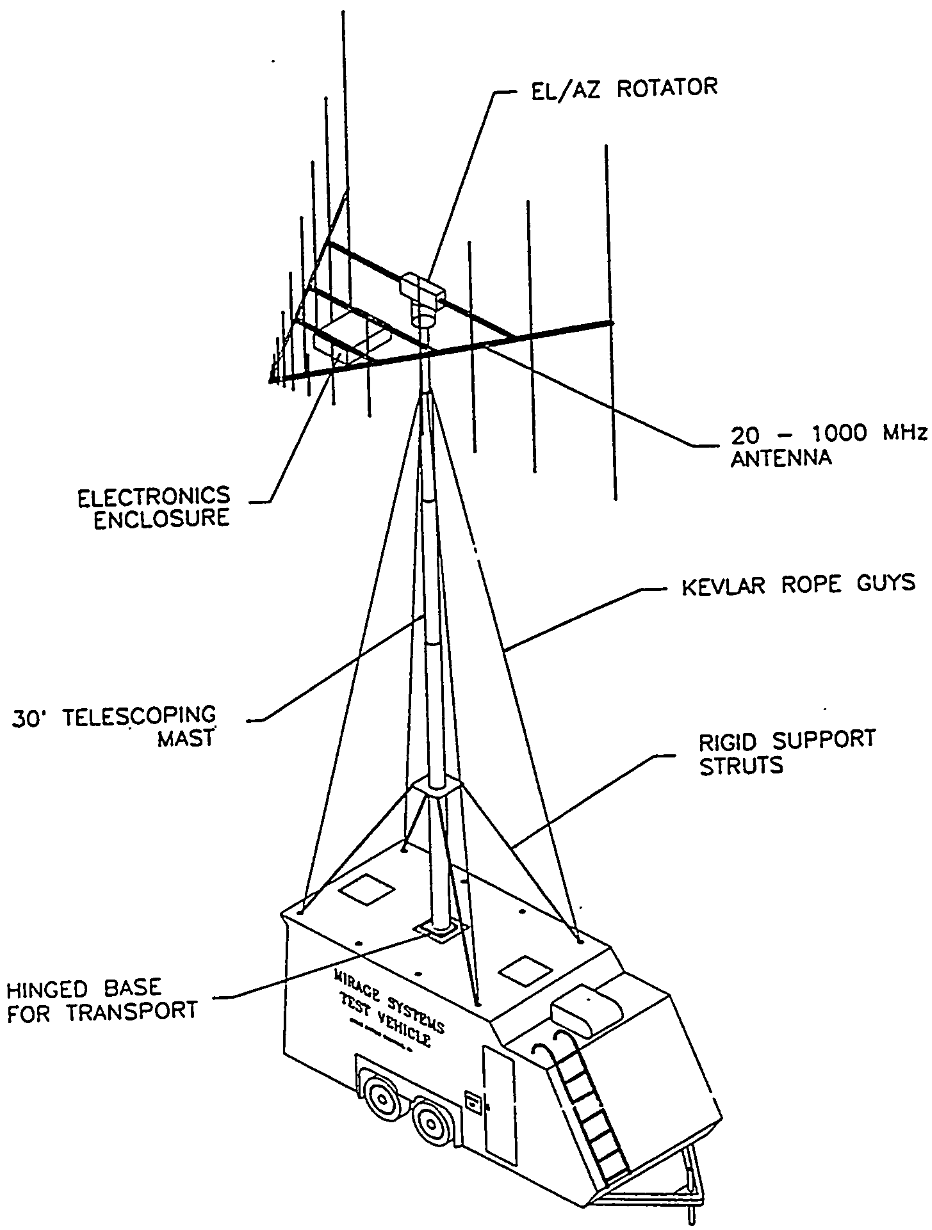

Figure 4. MTV configured with mast and antenna for test and evaluation

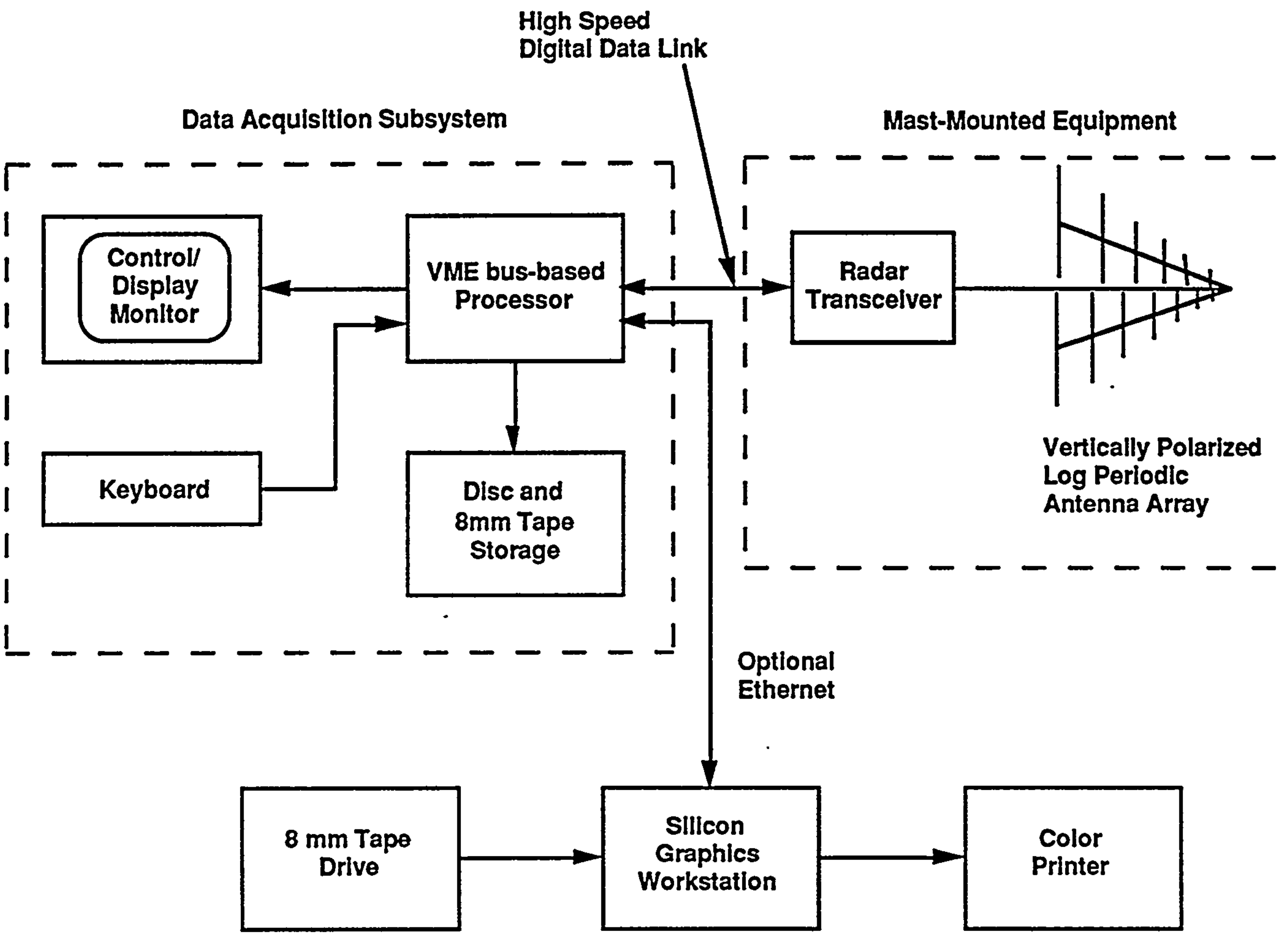

Figure 5. Simplified block diagram of the 3-D SISAR

Motion Compensation. Like all synthetic aperture radars, the 3-D SISAR operates by collecting a large amount of data that needs to be correlated over the dimensions of frequency, time, and space. While the frequency and time correlation is an internal function of the radar, a set of external reference repeaters are used to correlate the radar returns in the spatial dimension. A set of three repeaters positioned around the periphery of the surface of the imaged volume is used for calculating the physical relationship between the radar and the imaged volume of ground.

Graphics Display Workstation A Silicon Graphics model XZ workstation has been procured and is being used both as a software development platform and as a means to display and manipulate the processed images. This workstation has the necessary processing speed and graphics capabilities to compute and display the imaging data sets.

A three-dimensional digital imaging (3DDI) software program allows the operator to interact with the large data sets that comprise the images in a meaningful and efficient way. It provides the ability to render images in two and three dimensions, rotate and add perspective to images, encode image data with a range of colors, and threshold on intensity values. "AVS5" from Advanced Visual Systems was chosen for the image display and manipulation capability to extract position coordinates of objects within the rendered image of the underground volume.

Schedule

The remaining tasks on this project include the completion of the integration activities and the performance of the test and evaluation tasks. The testing will begin in early November, with the analysis of the collected data and additional imaging experiments continuing through the fall. At the completion of the experimentation, an evaluation demonstration will be scheduled for DOE personnel.

RESULTS

The test and evaluation phase of the project is just beginning, and the performance of the 3-D SISAR will be able to be demonstrated in the near future. To date, the images resulting from simulation and modeling tasks indicate that the basic assumptions underlying the imaging approach are sound. An example of a detected buried barrel was shown previously in Figure 2. The radar hardware has been assembled and tested, and is fully functional.

FUTURE WORK

It is envisioned that a subsequent expanded testing phase will be planned for further evaluation of the 3-D SISAR through exploring the potential of the imaging algorithms, learning about real-world remediation situations, and developing approaches for the optimal use of the 3-D SISAR during site operations.

Additional work in the image processing area consists of expanding the imaging algorithms to layered and graduated underground environments. The funding of the current contract provides for only limited testing, including several data collection experiments and a proof of concept demonstration. It is suggested that additional testing be performed during a future integrated technology demonstration at a prepared DOE site. This would provide a more complete performance evaluation of the 3-D SISAR under controlled circumstances.

SMALL BUSINESS PERSPECTIVES

As Mirage gains experience with contracting with DOE, there is a learning process involved with a new customer: understanding the DOE's needs, views, desires, and ways of doing business. METC has been very helpful in establishing a good working relationship that is oriented toward the success of the program, and in providing information of key government conferences, meetings, and contacts within the community.

This project is oriented toward technology development, and as the capabilities of the 3-D SISAR become established, it is important to look ahead at practical applications and use of this technology. It would be valuable for METC to assist Mirage with opportunities to better understand site cleanup operations and how this underground imaging method may be successfully integrated into site activities.

At this point of development, it is not apparent that there will be any regulatory or siting difficulties with the use of this technology, with one minor exception. The equipment does radiate a wideband, low power signal, and FCC licensing or type-approval may be required if the equipment enjoys broad use. The sponsorship and support of the DOE could expedite this process.

Small businesses can offer advantages to the DOE in terms of rapid development times and a higher degree of innovation. Often there is a higher degree of risk involved, since expanding the limits of the state of the art entails conquering unknowns and the unforeseen. Since small businesses often have limited resources to develop new technologies independently, technology transfer can provide critical support in achieving the objectives of a program.

During this project, one attempt was made at pursuing the transfer of imaging technology from a national laboratory. After six months, the attempt failed primarily because there does not exist an efficient path to accomplish this, and the contracting terms proved unworkable. Given more time and energy, the contracting difficulties could likely have been resolved. In this instance, however, the window of opportunity for the technology to have made a significant contribution to the project passed, and the effort was dropped from further consideration. No further plans for technology transfer are in place, but this does not preclude the pursuit of future agreements if the situation arises.

Because of its non-invasive, standoff imaging capability, the 3-D SISAR is seen to further DOE's goal of providing more cost-effective, safer technologies for underground imaging. As the 3-D SISAR evolves from concept to operational use, Mirage looks forward to the continued support and sponsorship of the DOE in fulfilling this goal.