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Technical Report

# Anti-Personnel Landmine (APL) Detection Technology Survey and Assessment

## Wide-Area Detection in Support of Arms Control

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Technical Report
March 1999

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Defense Threat Reduction Agency
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13. ABSTRACT *(Maximum 200 words)*

A survey was made of technologies and systems available to detect anti-personnel landmines for the purpose of monitoring or verifying a potential treaty-based landmine ban. A literature search revealed that numerous devices and supporting research exist for the point-source detection of anti-personnel landmines (APL), but only a few systems were found to be under development that address the more rapid detection of multiple APL and entire minefields over a wide area. Given the potential treaty verification need to be able to detect and describe the boundaries of existing and new APL use, and a complementary technical requirement in humanitarian demining, an assessment was made of those technologies that might be applicable to the wide-area detection mission, followed by the identification and assessment of pertinent systems. This survey identified certain promising RDT&E efforts, but none currently appear to provide a complete or near-term solution to the wide-area detection of landmines and minefields. A combination of sensors through sensor fusion and data fusion may hold promise for minefield detection with a higher degree of confidence. An investigation was also made of other technical disciplines not normally associated with landmine detection for the contribution they might make for the wide-area detection of landmines. None of the ten fields explored, however, offered any unique or more effective approaches or solutions to the mission. The study concludes with observations on the state of research and development in wide-area landmine detection and offers recommendations concerning the specification of technical requirements and for potential future initiatives in this field.

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| Hyperspectral Imagery | Magnetometry | CCD |
| LIDAR | Millimeter Wave Sensors | |
| Electromagnetic Induction | Cameras | |

# EXECUTIVE SUMMARY

This assessment report provides a response to Task 1 of the Statement of Work for Anti-Personnel Landmine (APL) Technology Assessment and Negotiation Support for the Convention on Conventional Weapons (CCW) and APL Control Regime under contract number DNA001-96-G-0061, Delivery Order Number 0001.

The first part of Task 1, called Assessment 1, comprised a survey and assessment of technologies in open source literature and from government and industry that might be applicable for APL detection and demining operations. These technologies were then rated as to their desirable and undesirable features. Initial findings indicated that fully funded RDT&E programs were already being performed by many organizations, both government and private, to address ground-based, point-target APL detection and demining. One area, however, in which significant work remains to be accomplished is in developing technical solutions to address the task of wide-area detection (WAD). The term "wide-area detection" is used to signify a capability to detect an APL minefield from a standoff distance and ultimately from an airborne platform. Technologies applicable to WAD can offer capabilities to both the arms control verification and humanitarian demining communities. The majority of this report consequently focuses on assessing, based on available information, technologies and their related systems that offer the potential to fully or partially fulfill wide-area detection requirements. In addition, information on the point-target detection and demining technologies uncovered during the initial research phase of the survey, while not pertinent to wide-area applications, is included in Appendix A.

The central finding of this initial assessment is that, although there is promising research, development, and testing occurring in WAD, no single technology or system presently provides a comprehensive solution to the challenge of detecting APL on a wide-area basis. The survey identified seven significant technology areas that may be applicable to WAD, including magnetometry, radar, infrared, millimeter wavelengths, visible wavelengths, light detection and ranging (LIDAR), and electromagnetic induction. Each of these technologies, however, has individual shortcomings based upon factors such as lighting or weather conditions, soil types, vegetation, or APL metal content. A synopsis of their wide-area detection potential is presented in Table ES-1. In addition, research on applications of these technologies revealed over three dozen systems that might have utility in WAD. But, like the technologies, each system has limitations that would preclude reliance upon any single existing system to solve the challenges of WAD.

Subsequent research (entitled Assessment 2), including site visits, of some of the most promising systems revealed that significant work is underway to address the challenges posed by WAD. Efforts investigated include the following:

- JAYCOR vehicle-mounted standoff landmine detection system
- AlliedSignal minefield reconnaissance and detector (MIRADOR) system
- Army Research Laboratory boom-mounted, ultra-wideband radar system
- Time Domain Systems, Inc. ultra-wideband radar system
- SRI International aerial detection systems
- Ongoing research efforts at the Canadian Defence Research Establishment Suffield
- Ongoing research efforts at the European Commission Joint Research Centre

**Table ES-1. Synopsis of wide-area detection potential of selected technologies.**

| TECHNOLOGY | Applicability for Monitoring Ban and Detecting Minefield Changes | Role in Humanitarian Demining Operations (HDO) and Unexploded Ordnance (UXO) Detection |
|---|---|---|
| Magnetometers/Gradiometers | Marginal; only good for close-in (point) detection | HDO - Marginal; effective for ferrous metal; problems with plastic and non-ferrous<br>UXO - Good point-source detection of ferrous metal |
| Radar | Good; potential for wide-area applications if resolution vs penetration, detection probability vs false alarm rate, clutter issues are solved | HDO and UXO - Good; possible problems with plastic in some soils |
| Infrared Sensors | Marginal to Good; potential for wide-area detection with limited obscurants; affected by duration of soil disturbance thermal effects | HDO and UXO - Marginal to Good, depending on system resolution |
| Millimeter Wave Sensors | Marginal to Good; potential for wide-area detection at slow scanning rate | HDO and UXO - Marginal to Good, depending on ability to discriminate mines from surroundings |
| Visible Light Sensors | Poor to Marginal; might detect surface changes, but easily obstructed, cannot see buried items | HDO and UXO - Poor; cannot detect buried items |
| Light Detection and Ranging (LIDAR) | Marginal; potential use for unobscured (surface) and recently emplaced mines | HDO and UXO - Marginal; can only detect surface-laid objects and the potential presence of recently placed explosives |
| Electromagnetic Induction | Marginal; only good for point detection of metal mines | HDO - Marginal; effective for metal mines, problems with plastic<br>UXO - Good point source metal detection |

- Lawrence Livermore National Laboratory micropower impulse radar (MIR)
- U.S. Army Airborne Standoff Minefield Detection System (ASTAMIDS)
- U.S. Marine Corps Coastal Battlefield Reconnaissance and Analysis (COBRA) system.

The investigation found that differing degrees of success have been achieved in the application of single technologies, each of which may provide a partial solution. Multi-technology systems are also being pursued where the complementary strengths of combined sensors may offer improvements in detection over the use of single sensors. Again, however, it was found that no system appears to provide a complete or adequate near- or mid-term solution for addressing wide-area detection of APL, although the most promising of these select systems warrant continued monitoring. Furthermore, because no agreed upon performance-based requirement has been promulgated against which these systems can be designed or evaluated, no accurate assessment can be made of the likely time frame in which they might achieve acceptable performance. A synopsis of Assessment 2 findings is provided in Table ES-2.

An investigation (entitled Assessment 3) was also made of disciplines not normally associated with landmine detection to determine how the technologies or systems used in those fields might be applicable to WAD. Information was sought from industrial, professional, academic, and governmental experts and information resources in these fields. The disciplines studied include:

- Geology
- Remote sensing
- Archeology/paleontology
- Medicine
- Astrophysics
- Explosive sensors
- Drug sensors
- Civil engineering
- Non-destructive evaluation
- Cameras.

Although some novel approaches were discovered or were suggested by technologists in these fields, many of the disciplines were found to rely upon technologies and even systems remarkably similar to those already found in APL detection and demining. Those technologies, too, face the same constraints driven by the underlying physics of the sensing devices and application scenarios. Again, there did not appear to be a single, fully developed, readily applicable answer to the problems posed by WAD. Findings of the assessment of the different disciplines are synopsized in Table ES-3.

The report also examines data fusion and technology fusion as potential solutions to the shortcomings of the individual technologies and applied systems. By combining functional features and information from one or more technologies or systems, the limitations of individual technologies or systems might be overcome or synergies might be created, thereby increasing detection rates and accuracy. However, data fusion may also impose an additional, potentially extensive data processing burden. The basic structure of data fusion algorithms is fairly uniform and not unique to any discipline, but the way in which those algorithms are employed is highly application-specific. Several institutions are engaged in the development and application of data fusion techniques, and there are commercially available signal processing software packages that perform data fusion. Overall, data fusion represents an important aspect of developing an effective solution to the challenges of WAD.

**Table ES-2. Synopsis of Assessment 2 findings.**

| SYSTEM | TECHNOLOGY | STATUS | APPLICABILITY TO WAD |
|---|---|---|---|
| JAYCOR Vehicle-mounted Standoff Landmine Detection System | Ground-penetrating radar (GPR); quantum-well forward-looking infrared (FLIR) to be added | Baseline testing to begin 8/97, advanced technology demonstrations to begin 6/98 | Poor to Marginal - vehicle-mounted, designed for detecting anti-tank landmines (ATL) |
| AlliedSignal Minefield Reconnaissance and Detector System (MIRADOR) | GPR and electro-magnetic induction (EMI), with infrared (IR) or visual camera | Work ceased March 1990, no further efforts planned at AlliedSignal; unit may be sent to Univ. of Missouri at Rolla | Poor to Marginal - vehicle-mounted; testing focussed on ATL detection |
| Army Research Laboratory Boom-mounted, Ultra-wideband Radar System | Ultra-wideband (UWB) GPR | Last tested at Aberdeen Proving Ground 10/96; currently addressing system improvements | Marginal to Good - must address limitations of single-technology approach and performance, translation to aerial platform |
| Time Domain Systems, Inc., Ultra-wideband Radar System | UWB GPR | Conceptual; no existing system; proof-of-principal testing performed | Marginal to Good - must address limitations of single-technology approach |
| SRI International Aerial Detection Systems | UWB SAR; addition of IR and hyperspectral under investigation | Three FOLPEN aerial detection systems operational, further tests pending; multi-sensor integration pending | Marginal to Good - must address limitations of single-technology approach |
| Canadian Defence Research Establishment Suffield Efforts | Hyperspectral imagery | Only preliminary testing to date of Compact Airborne Spectrographic Imager (CASI); improvements pending | Marginal - limited by single-technology approach; cannot detect buried mines |
| European Commission Joint Research Centre Efforts | Unknown; possibly some airborne systems | Details unavailable; possible use of U.S. sensors by DG-VIII office | Further information necessary for assessment |
| Lawrence Livermore National Laboratory Micropower Impulse Radar (MIR) | UWB GPR | Tested in prototype look-down array, primarily for point-source detection | Poor - single technology, extremely short detection range; only applicable for point source detection |
| U.S. Army Airborne Standoff Minefield Detection System (ASTAMIDS) | IR (passive and passive/active, respectively) | Two systems (Raytheon and Northrop Grumman) tested in 1996 for SSO application, found inadequate; further system developments on-going, FY98 transition to EMD phase | Marginal to Good - limited by reliance on one waverange (IR); designed for ATL detection |
| U.S. Marine Corps Coastal Battlefield Reconnaissance and Analysis (COBRA) | Multispectral video imagery | Field tests in August 1997; system improvements with commercially available equipment on-going | Marginal to Good - may be effective for coast, but requires daylight and cannot detect buried mines; designed for ATL minefield detection |

**Table ES-3. Synopsis of Assessment 3 findings.**

| DISCIPLINE | REPRESENTATIVE SENSORS | APPLICATIONS | POTENTIAL CONTRIBUTION TO WAD |
|---|---|---|---|
| Geology | Seismometers, gravimetric sensors, magnetometry, electromagnetic induction (EMI), resistivity, ground-penetrating radar (GPR) | Locating bedrock, underground features/voids, mineral and oil deposits; sensing tremors and nuclear tests; monitoring structure settlement | Poor to Marginal - Discipline addresses very-large-scale sensing, offers no unique detection contribution |
| Remote Sensing | LIDAR, hyperspectral, GPR, side-looking aerial radar (SLAR), infrared (IR), all other stand-off sensors | Land-, aerial-, and space-based sensing of man-made and natural phenomena from square-meter to global scale | Good - WAD *is* remote sensing, but discipline offers no unique detection advantages |
| Archeology/ Paleontology | Magnetometry, EMI, resistivity, GPR | Searches for buried bones, building and fossil remains, historical objects | Poor to Marginal - Discipline addresses small areas at a time, requires ground contact or proximity, offers no unique advantages |
| Medicine | Magnetic resonance imaging (MRI), X-ray, tomography, nuclear medicine, ultrasound | Non-intrusive investigation of human and animal tissues and internal organs | Poor - Requires scanned item to be between transmitter and receiver, or direct contact; discipline offers no unique advantages |
| Astrophysics | Optical sensors, SLAR, GPR, hyperspectral, LIDAR | Earth science physics investigates large-scale phenomena on earth's surface (crops, environmental conditions, large man-made structures and movements) | Poor - Discipline requires lower resolution than WAD, offers no unique advantages |
| Drug Sensors | Neutron backscatter, X-ray, thermal neutron activation (TNA), pulsed fast neutron, IR | Close-in detection of metal, non-metal, and organic materials associated with drugs and stand-off detection of drug production | Poor - Requires scanned material to be between transmitter and receiver or very close, or poor stand-off resolution; discipline offers no unique advantages |
| Explosive Sensors | X-ray, TNA, pulsed fast neutron | Detection of explosive materials or components associated with explosive devices | Poor - Requires scanned material to be between transmitter and receiver or very close; discipline offers no unique advantages |
| Non-Destructive Evaluation | All investigated sensors relevant to WAD, plus all other non-invasive proximate or contacting sensors | Investigation of presence or character of subsurface objects or conditions without damaging or consuming area or body surveyed | Marginal to Good - Discipline subsumes many WAD-related technologies but typically requires sensor proximity or contact; discipline offers no unique detection advantages |
| Civil Engineering | GPR, impact-echo, impulse response, spectral analysis of surface waves (SASW) | Search subsurfaces of man-made structures or load-bearing areas for voids, cracks, density changes | Poor to Marginal - Other than GPR, discipline typically requires sensor proximity or contact; discipline offers no unique advantages |
| Cameras | Film-based, charge-coupled device (CCD), and active pixel sensor visible or IR wavelength sensors; spectral filters | Image collection in visible and IR wavelengths | Poor to Marginal - Mature sensors easily obstructed, potential complement to sensor suite; discipline offers no unique advantages |

Of the technologies investigated in this report, three are evaluated to be more developmentally advanced, their applications are better understood, or they are better suited overall to wide-area detection. They are:

- Ultra-wideband, ground-penetrating, synthetic aperture radar
- Infrared sensing
- Hyperspectral imagery.

These three technologies received the most attention from researchers surveyed and were cited most often in technical publications addressing wide-area detection. Research and development efforts involving their use or integration into different systems bear continued monitoring.

This study also identified a need for the establishment of uniform, validated, and accepted technical requirements for the wide-area landmine detection mission. These requirements would provide a basis for effectively developing and evaluating new systems. There would probably be two sets of slightly different requirements - one for monitoring and verifying an APL ban and another for humanitarian demining - for which there would be significant commonality, although they would not be identical. Their formulation could be undertaken jointly by representatives of the arms control and demining communities, technical developers, and technology policy makers.

Ancillary to the above findings, certain observations were made regarding the oversight and coordination of the many disparate RDT&E efforts addressing landmine detection, including WAD. These evolving initiatives may benefit from the application of an overarching, concerted approach for developing landmine detection systems. To ensure a broader and more comprehensive search for solutions, it is recommended that a coordinated, systematic methodology for investigating and assessing potential technical approaches, sensor combinations, integration techniques, and deployment approaches be considered for development. These observations, while derived from a totally different assessment methodology, underscore the conclusions of the September 1995 GAO Report on Unexploded Ordnance. The DoD's Report to Congress - Unexploded Ordnance Clearance, dated 25 March 1997, states changes have been implemented to address this situation across all of the functional areas involved. The organization to be employed is the Joint UXO Coordination Office, established on 1 October 1997 as the operational arm of the UXO Center of Excellence and collocated with the Night Vision Electronic Sensors Directorate at Fort Belvoir, VA. Moreover, it may be desirable to assess and monitor, and potentially coordinate with, other on-going WAD technology development initiatives such as DoD's five multi-university research initiatives (MURIs), as well as the Joint UXO Coordination Office.

PREFACE

This report was conducted by DynMeridian's Strategic Technologies and Arms Control Analysis Division on behalf of the Defense Special Weapons Agency (DSWA) to assist the Department of Defense in assessing the technologies and systems applicable to anti-personnel landmine detection and demining. Specifically, this report documents a literature search and technology assessment performed for DSWA under Contract DNA001-96-G-0061, Delivery Order No. 001 under the supervision of the Office of Arms Control Technology Program. John Deni, Churchill Hutton, Richard Johnson, David Kerner, and Tom Kincaid performed the research and evaluation of technologies and systems available to detect anti-personnel landmines for the purpose of verifying a potential treaty-based landmine ban. Joseph Grubb was Program Manager for this effort. Requests for additional copies, as well as questions or suggestions regarding this assessment, should be addressed to the DSWA Program Manager for this effort, Ms. Diane Steinberger, DSWA/PMA at (703) 325-1309.

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# SECTION 1

# LANDMINES AND DEMINING

## 1.1 INTRODUCTION.

This assessment report provides a response to Task 1 of the Statement of Work for Anti-Personnel Landmine (APL) Technology Assessment and Negotiation Support for the Convention on Conventional Weapons (CCW) and APL Control Regime under contract number DNA001-96-G-0061, Delivery Order Number 0001. The first part of Task 1, called Assessment 1, comprised a survey and assessment of technologies in open source literature and in materials provided by government and industry that might be applicable for APL detection and demining operations. Assessment 1 is presented in Sections 2 and 3 of this report. Assessment 1 findings indicate much effort is needed in the area of wide-area detection, wherein large areas of land might be surveyed rapidly and at a safe stand-off distance. The majority of this report consequently focuses on assessing, based on available information, technologies and their related systems that offer the potential to fully or partially fulfill wide-area detection requirements.

Report Section 5 discusses subsequent research (entitled Assessment 2) made of some of the most promising systems identified in Assessment 1. In a parallel investigation (entitled Assessment 3), disciplines not normally associated with landmine detection were assessed to determine how the technologies or systems used in those fields might be applicable to WAD; this effort is described in Section 6. In addition, the report also examines data fusion and technology fusion in Section 4 as potential solutions to the shortcomings of the individual technologies and applied systems.

This report section (Section 1) provides a foundation for assessing the potential of various landmine detection technologies and systems to support a possible monitoring regime for an APL ban. To better understand the direction arms control monitoring technology development could take, it is necessary to describe the baseline of APL-related activities today. First, the threat posed by landmines and the techniques and methodologies established by the military for countermine and humanitarian demining operations are briefly reviewed. An examination of some of the other major influences driving technological developments completes the description of the APL baseline. The section concludes with a discussion of the materiel requirements necessary to support arms control verification and humanitarian demining, along with an explanation of how wide-area detection (WAD) technologies may play a role in demining and in monitoring a treaty to ban APL, establishing WAD as the subsequent focus of the remaining sections of the report.

## 1.2 THE THREAT.

A brief look at the threat is useful to fully understand detection and demining technology needs. Anti-personnel landmines range in size from several ounces to four or five pounds. Anti-tank landmines (ATL) can be found with weights from about four pounds to over 30. Net explosive weights range from one ounce to about a pound for anti-personnel landmines, while anti-tank landmines can contain from one pound of explosive to over 20 pounds. Both types can either contain significant amounts of metal or can be almost completely non-metallic. The non-metallic (or minimum metal content) landmines are difficult to detect with the detection systems currently in service.Fuzes (or firing trains) are the mechanisms within the landmine that trigger an explosion. These devices can be very simple, such as a pressure plate that causes detonation when stepped on by a human.

Conversely, fuses can also be extremely complex electronic circuits, such as devices that cause detonation when they detect changes in the magnetic field around the landmine. Landmines can have single or multiple fuzes, and they can contain secondary fuze wells permitting booby-trapping (or the installation of anti-handling devices) to prevent easy removal from the ground.

Hand-emplaced landmines used by "responsible" military forces are normally laid in patterns and their locations mapped to allow removal or destruction after their military purpose has been served. In low intensity conflict or in unconventional warfare, landmines are often the weapon of choice because of their availability, low cost, ease of use, and effectiveness against dismounted troops. Although anti-tank landmines could be present in any combat situation where landmines are used, anti-personnel landmines are the most prevalent types encountered in less-developed countries. Typically, landmines used in less-developed countries have the following characteristics:

- Anti-personnel, under 3 lb. total weight;
- Plastic (non-metallic) body; minimum quantity of metal in the firing train;
- Randomly laid, locations not recorded;
- Placed around civilian as well as military targets;
- Placed one at a time by hand; and,
- Potentially placed around anti-tank landmines.

## 1.3 COUNTERMINE OPERATIONS.

Military countermine operations have two distinct operations—breaching and area clearance. Both are conducted solely to enable combat operations to proceed, but breaching occurs more often under fire. For example, if a mechanized force needs to overcome a complex obstacle, including anti-tank and anti-personnel landmines, and continue an attack toward a distant objective, a breach in the obstacle will be attempted in at least two places without a decrease in the pace of the offense. The breach will be just wide enough to allow passage of single vehicles, in column, and as much as 20 percent of the landmines may remain in the breach lane. Dismounted troops employ similar breaching techniques to move through areas strewn with anti-personnel landmines. In both cases, the goal of breaching is to move as quickly as possible through an obstacle, regardless of whether all of the landmines were detected and removed.

Though area clearance is also conducted in connection with combat operations, it is rarely done under fire. An example may be to clear mined terrain for a headquarters or logistical location necessary to support operations. Here, the landmine detection and removal rates must be much higher than in a breaching operations and time is not as much a constraint. In some situations, rather than take the time and risk of exposure to casualties involved in conducting an area clearance, it is often simpler to seek alternate, unmined locations. Minefields will be marked and avoided whenever possible and the job of dealing with the residual war hazard left until after the cessation of hostilities.

## 1.4 DEMINING.

Minefields and other areas contaminated with explosives have been treated as one of the consequences of war left to the host nation to resolve. Internal, low intensity conflicts around the world over the last two decades have left a legacy of mostly anti-personnel landmines. The problem of eliminating this threat, known as "demining," is being addressed as a humanitarian issue. "Demining" is the term used to distinguish the non-combat oriented removal of landmines from traditional countermine operations. In many respects though, with the notable exception of the victims of landmines left from a war that may have already ended, the demining mission is quite similar to the military area clearance mission. To meet the challenges of humanitarian demining and area clearance, the tools developed by the military for dismounted breaching have been applied in various countries around the world.

## 1.5 TASKS.

There are five tasks usually associated with military countermine operations (breaching and area clearance) and, with minor redefinition, associated with demining:

### 1.5.1 Detection.

The first requirement is to locate the mined area and its boundaries, then find individual landmines. When using any automated or standoff system, a significant challenge is to accurately identify objects as explosive items from a distance and then to reacquire their location on the ground. Included in the detection function are the sub-tasks of locating, identifying and evaluating the target once detected; within the scientific community, these sub-tasks are occasionally considered separate from the detection task.

### 1.5.2 Marking.

Like detection, the requirement is to first mark the minefield boundaries, then the individual landmines. Marking requirements range from delineating areas on maps to posting signs and barriers around minefields to marking individual landmines for removal or destruction. In U.S. Army doctrine, reporting enemy minefields is listed as a separate task, but in humanitarian demining operations reporting enemy minefields is included in the overall marking task.

### 1.5.3 Neutralization.

In some environments, access to minefields and individual landmines can pose such a great challenge to demining that it may be treated as another requirement in technology development. Since gaining access, such as physically reaching a mined area or removing brush and earth around an individual mine, immediately precedes neutralization, access will be treated in this report as a sub-task of neutralization.

When dealing with large minefields and when using well-trained personnel, individual landmines can be safely removed from the ground, aggregated in one location, and destroyed. However, this poses the potential for landmines to be stockpiled and reused later. Removal also poses some degree of increased risk to personnel and requires a higher degree of skill than individual in situ destruction of landmines. The policy guidance found in the Department of Defense (DoD) Humanitarian Demining Program directs U.S. military forces to destroy landmines in place with an explosive charge.

### 1.5.4 Proofing.

Before using a formerly contaminated or mined area, some form of quality control must be conducted to assess the risk to personnel. There is no universally accepted method to proof a location after area clearance has been conducted nor is there agreement on clearance standards. Mechanized devices, like the rollers used to detect landmines when breaching, can be used for proofing, as well as the electronic detectors used for area or localized searches.

### 1.5.5 Protection.

Protection of personnel and equipment is a consideration in all four preceding tasks, though it is not treated as a separate task in U.S. Army countermine doctrine. Some protection is provided in mechanized operations since such vehicles are usually armored. In dismounted operations, flak jackets and helmets, along with some commercially procured personnel protective clothing, offer limited protection. Since blast effects dissipate rapidly in air, performing any of the other four tasks from standoff distances has major benefits.

## 1.6 EQUIPMENT CURRENTLY IN USE.

The tools and equipment applied to demining thus far have been based upon tactical combat needs and therefore lack a broad-area or country-wide orientation. From a tactical standpoint, the tools and equipment are needed to locate the boundaries of minefields, find individual landmines and then destroy them. Such equipment, however, is poorly suited for dealing with the challenges posed by an entire country contaminated with landmines or by a global need to determine the absence or presence of APL.

The specific equipment presently used for humanitarian demining by U.S. Forces and items available as prototypes or in limited production are described below according to demining task.

### 1.6.1 Detection/Proofing.

When mounted on armored vehicles, steel rollers pushed in front of tanks are used to detect minefields. Rollers can also be used to proof a breached passageway or a road. A magnetometer, or some other type of metal-detecting instrument, is then used by dismounted soldiers to locate individual landmines. If non-metallic (or minimum metal content) landmines are suspected, dismounted soldiers must then perform hand probing with long rods. Specific detection tools and approaches include the following:

- Hand-held detectors: The Schiebel AN-19/2 (AN/PSS-12) metallic landmine detector uses eddy-current technology. There are other eddy current detectors and magnetometers on the market produced by companies like Vallon, Forester, and Ebinger. All are limited in their capability to detect minimum metal content landmines reliably and none can detect completely non-metallic landmines.

- Vehicle mounted detectors: By adapting larger versions of the hand-held technologies (like the Schiebel) to vehicle mounted applications, the time necessary to detect landmines over a given area decreases dramatically. Such instruments have been mounted on landmine blast resistant vehicles to increase survivability and are being considered for use in road clearance operations.

- Airborne Standoff Minefield Detection: The <u>A</u>irborne <u>STA</u>ndoff <u>MI</u>nefield <u>D</u>etection <u>S</u>ystem (ASTAMIDS) program of the U.S. Army Project Manager for Mines, Countermine, and

Demolitions is in the “Demonstration Validation” phase of development involving two competing contractors—Northrop-Grumman and Raytheon. The program could enter production by 2000. This system will focus on detecting minefields, not individual landmines. The ASTAMIDS program is addressed in greater detail later in this report.

- Dogs: Dogs are extremely reliable landmine detectors, though inclement weather, poor terrain, and care and health issues often prove to be major limitations. RONCO Consulting Corporation in the U.S. and Mechem in South Africa are the leaders in the use of dogs for landmine detection. Dogs can be used either in a free-ranging mode to find a point source (landmine) or they can be used in conjunction with a vehicle mounted air sampler to provide area detection. Mechem has developed a system based on the latter application, which is addressed in greater detail later in this report.

### 1.6.2 Marking.

The U.S. military employs relatively simple, standardized methods and equipment for marking. For example, minefield boundaries are often marked with pickets holding internationally recognized warning signs. Problems arise when, in some developing countries, materials used in marking become more valuable to local residents for other purposes. In Northwest Somalia , for instance, steel pickets were used by Rimfire, Ltd. (a firm from the United Kingdom) to mark minefield boundaries. The pickets were later removed by local residents and used to construct dwellings.

In some cases, it is possible to couple paint spray devices or other marking devices to vehicular or man-portable detectors to provide a mark on the ground.

Locating a minefield from a standoff distance is only useful if the minefield location can later be pinpointed by those on the ground. Linking a landmine detector to a Global Positioning System (GPS) can bridge the gap between standoff detection and marking.

- Military systems: The Cleared Lane Marking System (CLAMS), mounted on the M1/M1A1 tank, and the M133 hand emplaced minefield marking set (HEMMS) were developed by the U.S. for marking a breached passageway and have little application to humanitarian demining. The devices are used to provide temporary lane marking only in a tactical situation and are not suitable for longer-term applications. There are other military systems like the Pathfinder, developed by the United Kingdom, but they too are intended for military breaching applications.

- Commercial: Non-military marking methods are generally locally improvised from available materiels. Plastic tape (similar to tape used by police departments in the U.S. to mark off crime scenes) is available commercially and can usually be found with warning messages printed in a variety of languages.

### 1.6.3 Neutralization.

Prior to neutralizing a landmine, access to the mined area and individual landmines must be gained. This is a task best performed using common hand tools like grapnels, machetes, shovels and trowels. Chain saws, commonly used motorized garden equipment, and other mechanical devices have applicability only when the possibility of direct contact with a landmine is remote. Only after the landmine is exposed and positively identified can it be reliably neutralized.

There are two reasons why the most common method of neutralization is destruction in place. First, this method is inherently safer than removing the landmine and transporting it elsewhere for neutralization, and second, this method requires less training and skill on the part of deminers.

- Explosive destruction: Normally the explosive charges used for individual landmine destruction are standard military explosives, such as TNT, Composition C-4 and Semtex. In order to avoid providing bulk explosives to countries emerging from internal conflicts, the U.S. is exploring options like specialized commercially available explosive charges. Small shaped charges used in the oil drilling industry provide sufficient force to destroy landmines in place, are of little use as a bulk explosive, and are relatively inexpensive.

- Breaching Tools: Traditional military countermine breaching equipment, including the Full Width Mine Rake, the Mine Clearing Blade (MCB), armored kits for bulldozers, M1A1 Bangalore torpedoes, M58A4 Mine Clearing Line Charge (MICLIC), Anti-Personnel Obstacle Breaching System (APOBS), and the Barrett 0.50 caliber semi-automatic assault rifle have almost no use in humanitarian demining.

- Flails: Typically, flails clear an area by rotating a steel shaft with chains affixed to the shaft and “hammers” attached at the end of each chain. When the “hammers” contact landmines, the intended result is a detonation, though the landmine may simply be broken apart and its components scattered throughout the area, creating a hazardous byproduct. Effective depth of clearance by a flail is about one foot. Flails have been proposed as a tool for landmine neutralization since early in World War II. They can be effective in breaching operations, but none have proven very useful in humanitarian demining. Types of flails include:

  - Aardvark: Developed in the United Kingdom, the Aardvark was used in Kuwait after the Persian Gulf War with little success. It clears a path three meters wide at a speed of about one kilometer per hour. Aardvark’s designers claim it can withstand detonation of a landmine with 10 kilogram net explosive weight. Cost is estimated in excess of $560,000.

  - Keiler: The Keiler, developed for the German government, is attached to a tank chassis (most commonly, the U.S. M-48A2). One of the two prototypes developed is currently in use by units of the North Atlantic Treaty Organization’s Stabilization Force in the former Yugoslavia. In March 1994, the developer, MaK System GmbH, was contracted by the German government to produce 24 Keiler landmine clearing vehicles. The clearing speed is advertised at up to four kilometers per hour. Replacement of the clearing “hammers” is necessary after about 3000 meters clearance in medium to heavy soil. When offered to the U.S. for use in Operation Desert Storm, the cost of the two prototypes was reported as $2 million, not including the tank to which the flail system is attached.

  - Miki: The Miki is a flail developed in Israel, primarily for use on the Golan heights. It too is mounted on a tank chassis and there is at least one working prototype. The cost is comparable to the Keiler.

  - Trail Flail or Mini Flail: The Countermine Division at Fort Belvoir developed a mini flail several years ago for use by special operations forces in Central America. Its intended use is to clear narrow trails. Mounted on a commercial Bobcat chassis, it is tele-operated and costs about $175,000-200,000. Two prototypes have been sent to Europe for use by the U.S. Army in Bosnia.

- ‣ Runway Clearance: The Swedes built a prototype flail which swings weights horizontally as opposed to the vertical orientation of the other flails described above. The Israelis also have built a prototype mechanical runway clearance device. They are both designed to clear landmines from the surface and will not remove any subsurface items. Such systems have very little applicability to demining, but work well in clearing landmines and submunitions from hard surfaces like airfield runways.

- Land Clearance Devices: These machines, usually attached to armored vehicles, essentially grind up soil, vegetation, and landmines with large rotating steel cutters. These systems have not been fully evaluated for landmine clearance. Risks of these types of machines are that they can create erosion problems, and that in some cases they can also displace landmines, creating hazardous duds. One system developed in Sweden uses the chassis from a Leopard I tank and cultivates soil down to a depth of about 50 centimeters. The machine is being developed by the Bofors Company with funding from the Swedish Foreign Aid Agency. It is advertised as being capable of clearing 10 square kilometers per week and of withstanding the effects of 10 kilograms net explosive weight. A similar device has been developed by the Swedish company BOA in cooperation with the U.S. firm, Caterpillar, and is mounted on a bulldozer.

### 1.6.4 Protection.

Proximity to landmines during each of the operational tasks of demining necessitates differing levels of protection depending on whether deminers are working on foot or from vehicles.

- Personnel: Equipment used to protect deminers usually consists of helmets with lexan face shields, “flak” jackets and shin guards. Natick Laboratories in Massachusetts has developed an ensemble for use by deminers, but it is bulky and relatively expensive for humanitarian demining. Other commercially available specialized protective items include large “snowshoe” type devices that disperse weight. Generally, nothing provides dismounted deminers absolute protection from the effects of a landmine. At best, personnel wearing protective equipment are provided some degree of protection from an explosion caused by another deminer—direct contact with a landmine is almost always injurious.

  Operating at standoff distances can provide substantial protection for deminers. Tele-operated detection equipment dramatically reduces the chances of landmine exposure for deminers. Tele-operation or robotic kits have been produced in Israel and the U.S.

- Vehicles: Landmine blast resistant vehicles that can transport personnel safely through mined areas are not common. South Africa has the most experience in developing such vehicles, but until recently, economic embargoes precluded the spread of this technology. The South Africans have produced articulated vehicles with “V”-shaped hulls, which are advertised to withstand the blast of one (or more) large anti-tank landmines.

## 1.7 INFLUENCES DRIVING TECHNOLOGICAL DEVELOPMENTS.

The Department of Defense Humanitarian Demining Program Strategic Plan establishes the goal and supporting objectives relating to development of equipment for humanitarian demining. It states, “The materiel acquisition program should focus on inexpensive and simple-to-operate equipment with a level of technology appropriate to use in the host nation." While high technology solutions may be mandated for specialized tasks, the intent of the plan is to provide relatively uncomplicated equipment that is transferred to the host nation for use and sustainment. The plan also specifies a strategy to implement the goal by establishing "a method to portray user requirements for materiel and data so focus is maintained at the appropriate level for host nations."

In FY 1995, Congress authorized and appropriated $10 million to the U.S. Army countermine advanced development program to be used "for Army efforts to improve landmine detection and neutralization, with emphasis on technologies that can be shared in an international environment."[1] This evolved into a one-year program designed to "demonstrate technologies, techniques, and equipment that make demining operations safer, more cost effective, and manpower/training effective."[2]

In December 1994, the U.S. Army Communications & Electronics Command, Night Vision and Electronic Sensors Directorate issued a Broad Area Announcement titled "Countermine for Demining in Operations Other Than War."[3] The objective of the program was to develop and demonstrate countermine technologies to detect, identify, mark and clear landmines in operations other than war. The program also emphasized the development of technologies that could be shared in an international environment. Proposals were specifically requested in the following areas:

- Airborne Detection and Reconnaissance: increase timeliness and reduce costs of landmine/minefield detection; locate and plot locations; rapidly transfer data into ground coordinates; consist primarily of electro-optical sensors; have DGPS; cue targets automatically; have additional secondary detection and verification by high resolution aerial mapping camera;

- Vehicular Mounted Mine Detector—Off Road: permit remote control; operate in moderately rough terrain; demonstrate performance of all proposed sensors; detect over path width greater than or equal to 1.5 meters within 5 cm; physically mark or electronically store APL locations;

- Vehicular Mounted Mine Detector—On Route: permit remote control; demonstrate performance of all proposed sensors; detect over path width greater than or equal to 2 meters wide; physically mark or electronically store APL locations;

- Mechanical Clearance: mount on a tele-operated vehicle; cover total area indiscriminately or find individual landmines; equip with articulated beam; protect with armor; allow high maneuverability;

- *In-Situ* Neutralization: require minimal training; reduce cost; incorporate lightweight, highly reliable, fixed time delay explosive device; and,

- Protective Vehicles: reduce cost; permit incorporation of commercial or military vehicles produced in other countries; quantify performance against ATL and APL.

Successful offerors were required to develop, fabricate, demonstrate and deliver at least one experimental system. Participation in testing at a government site and the analysis of survey data leading to delivery of a technical report were required.

To provide further direction for the research and development effort, the agency charged with executing the program, the Night Vision and Electronic Sensors Directorate at Fort Belvoir, sponsored a workshop on January 18-19, 1995. The attendees represented the regional Commanders-in-Chief (CINCs) who operate the DoD Humanitarian Demining Program in host nations. Among the briefings on policy, intelligence, and material development initiatives, the attendees reviewed the requirements for humanitarian demining outlined recently by the United Nations Demining Experts:[4]

- Must clear 50 times faster than present rates;
- No more than five times present costs;
- Preferred clearance costs should not exceed $.02-.03 per square meter;
- Simple enough to be operated by indigenous people;
- Clear down to 30 cm depth;
- Provide crew protection against 12 kilogram AT landmine blast;
- Work in at least 90 percent of all soil conditions;
- Function on side slopes of up to 30 degrees;
- Easily transportable and have mean time between failure (MTBF) of no more (less) than 300 hours;
- Detectors cost less than $4,500 with 90% probability of detection; and,
- Detect lone buried landmines and 4 cm plastic landmines.

As a result of the Broad Area Announcement and the Workshop, about thirty technologies or applications were considered in the Fiscal Year 1995 Army research and development program. A list of the items follows: [5]

*On-Road and Off-Road Detection*
Vehicle Mounted Detection System
Vehicle Mounted Mine Detection (VMMD)
Ground Based Quality Assurance

*Mine Clearance*
Tele-operated Ordnance Disposal System (TODS)
Mini-Flail

*In-Situ Neutralization*
Explosive Demining Device (EDD)
LEXFOAM
Chemical Neutralization of Landmines
Landmine Marking and Neutralization
Shaped Charges

*Individual Components*
Modular Vehicle Protection (MPV) Kit
Blast Protected Vehicle
Mobile Training System
Mini Landmine Detector
Extended Length Probe
Extended Length Weedeater
PSS-12 Landmine Location Marker
Blast and Fragment Containers
Demining Kit
Berm Processing Assembly
Landmine Clearing Blades

Grapnels
Handheld Trip Wire Detectors
Vehicle Towed Roller
Command Communications Video and Light System (CCVLS)
Mobile Video and Light System (MVLS)
Side Scan Sonar
K9 Program

The Assistant Secretary of Defense for Special Operations and Low Intensity Conflict released an "Equipment Planning Guide" on August 1, 1997. The stated purpose of the Guide is to provide "a listing of the tools and equipment currently considered applicable for use in the United States Department of Defense Humanitarian Demining Program." The document serves as a baseline to define the current state-of-the-art in tools available for demining. Most of the equipment is from military sources. For many items, there are similar commercial substitutes and the Guide can serve as an aid in procuring them.

The 1992 version of the U.S. Army Countermine Modernization Plan was updated in 1997 and is now titled "U.S. Army Countermine Modernization Strategy."[6] The modernization plans do not provide any new equipment for accomplishment of the area clearance/demining tasks beyond the ones shown in the Planning Guide and the R&D Program. As in the past, some equipment developed for breaching (particularly dismounted breaching) will probably be applied to the demining task. The updated Countermine Strategy cites military marking, clearing and protection tactical programs, but funding remains unclear.

## 1.8 REQUIREMENTS FOR TREATY MONITORING AND DEMINING.

Humanitarian demining is a relatively new endeavor for the U.S. military and objectives, or more specifically, materiel requirements, for demining have not been clearly defined. Similarly, until negotiated, ratified, and entered into force, the monitoring or verification requirements of an APL ban are not fully known; however, in order to provide technical support to negotiations and to be prepared to field technologies for an often short-fuse entry-into-force planning timeline, potential requirements must be scoped and research and development conducted to ensure the USG enters into an agreement it can comply with in the timelines demanded.

Requirements for each task in humanitarian demining, and for the potential tasks associated with monitoring and verification of an APL ban, need to be formulated. Then, validation and approval of requirements by the appropriate Department of Defense proponent should be the first step in the research and development process. With firm requirements, developers will have concrete goals and measures of success, and an independent tester will have standards for measuring and comparing performance, even in the basic research stage.

### 1.8.1 Improved Landmine Detection Capabilities.

The first step in being able to monitor a ban on APL use or in clearing landmines from a country or region is to bound the extent of the problem by determining the locations of mined areas. The determination of areas free of landmines and unexploded ordnance (UXO) is just as important to the demining effort as finding minefields. Logically, four categories can be assigned to geographical areas: 1) confirmed mined; 2) suspected to be mined; 3) suspected to be clear; and 4) confirmed clear. A complete survey of the country or region will result in placing all areas into one of the four categories. Once the extent of contamination is known, priorities for clearance can be established and the task of detecting and removing individual landmines can start for humanitarian demining. Similarly, this establishes a baseline for monitoring future compliance with a ban on APL use.

Requirements differ, however, depending on the magnitude of the search for anti-personnel landmines. For instance, a device designed and used to search one square meter of land for APL and a device designed and used to search one million square meters would have very different performance demands. Thus, there are different sets of requirements for different modes of APL detection. These types of detection are roughly grouped into three different categories—hand-held detection, vehicle-mounted detection, and wide-area detection, implying a stand-off capability beyond that achievable from a vehicle platform and wherein large areas of land can be surveyed rapidly. Because of the similarities between demining and military countermine, ongoing military programs can serve as a point of departure.

1.8.1.1 Handheld Detectors. The U.S. Army has a program to develop a "lightweight, handheld, metallic/nonmetallic, standoff landmine detector to replace the AN/PSS-12 landmine detector."[7] The AN/PSS-12 employs an electromagnetic induction sensor and will only detect metallic landmines. The AN/PSS-12, manufactured by Schiebel in Austria, is used by several demining organizations. There are other detectors used in demining with capabilities similar to the Schiebel, such as those produced by Vallon or Forester. Such point target detection systems can detect low-metallic content landmines to varying degrees depending on landmine orientation, soil type and weather conditions.

The significant improvement sought in replacements to the AN/PSS-12 is the capability to detect both metallic and nonmetallic landmines from standoff distances. Unlike the new Handheld Standoff Mine Detector System (HSTAMIDS), the AN/PSS-12 detects landmines within inches of the detector head; the HSTAMIDS will alert the operator of a suspected landmine from a distance of 3 meters. Although weighing in at thirty-five pounds, the HSTAMIDS will integrate two or more sensors and have a built-in test capability.

The HSTAMIDS program has made significant progress in the last two years, and the Department of Defense estimates that mass produced units will be in the hands of U.S. soldiers by 2002. Funding for the HSTAMIDS program was projected to be $29.1 million in research, development, testing and evaluation (RDT&E) funds.[8]

Though HSTAMIDS appears to be technically suitable for humanitarian demining, a lighter detector with the same detection capabilities would be better suited to the demining mission, since humanitarian deminers may not always have the physical capabilities of U.S. soldiers. Cost will also be a factor. Conceptually, the detector will use two sensors and processors which, parametrically projecting the cost based on today's detectors, means the HSTAMIDS will probably cost around $4,500 to $5,000. Equipping a humanitarian demining force across an entire country with the HSTAMIDS would be prohibitively expensive for many developing countries. Finally, the HSTAMIDS program has requirements pertaining to military logistics support that, though an important element, may be more extensive than needed in a humanitarian demining operation.

1.8.1.2 Vehicle-Mounted Detectors. The U.S. Army has a stated requirement for a "tele-operated, vehicle mounted, metallic and/or nonmetallic landmine detection and marking system."[9] The objective of the Ground Standoff Mine Detector System (GSTAMIDS) is to detect and mark landmines for reconnaissance forces and convoys and to detect the leading edge of minefields for follow-on breach teams. The experience of U.S. military forces in Somalia and Bosnia clearly indicated that current methods of detecting landmines in roads, for instance—by visual observation and by using hand-held detectors—are inadequate.

No capability to perform this mission exists in the U.S. military, though there are some candidate non-developmental systems available to provide a solution in the short term. One program being developed under GSTAMIDS is supported by $1.98 million in Foreign Comparative Test funds, $2.5 million in RDT&E funds, and $15.6 million in Procurement funds.[10] A follow-on program is being developed by the U.S. Army.

Since the GSTAMIDS will be mounted on a blast-resistant vehicle capable of withstanding the effects of an anti-personnel landmine and most, if not all, anti-tank landmines, the military mission profile and requirement is similar to what would be required to clear roads of landmines in humanitarian demining missions. But as with other systems developed by the military, integrated logistics support requirements may be more elaborate than required for humanitarian demining. Despite such minor differences between requirements for military missions and humanitarian demining missions, the GSTAMIDS programs now undergoing evaluation by the U.S. Army could be purchased for a humanitarian demining application today if a validated need existed.

1.8.1.3 Wide-Area Detectors. Country-wide surveys are presently conducted by sending teams of interviewers to gather information about the location of landmines and minefields from the local populace. This is a labor-intensive and time-consuming task. Mined areas must be more quickly identified in order to assign priorities for clearance and clear areas must be more quickly identified to permit productive land use. Therefore, the first objective in wide-area humanitarian demining, as well as arms control compliance monitoring, should be to decrease the time required to survey a country by augmenting or replacing the current individual interview techniques.

The United Nations International Conference on Mine Clearance Technology held July 2-4, 1996 in Copenhagen, Denmark highlighted the need for a wide-area detection capability to improve on current practice. (This need is reinforced by a May 1997 Doctors Without Borders report describing the landmine situation in Afghanistan.[11]) Many delegates spoke of the inadequate, inconsistent and incorrect information that often results from interviews and surveys. At the same time, delegates expressed a inability to research, develop and field an airborne detection system for humanitarian demining. As a result of the Copenhagen Conference, the United Nations published international standards to “provide a framework for the creation of Standard Operating Procedures (SOPs), which in turn detail the manner in which specific mine clearance operations are conducted.”[12] The international standards outline three levels of survey “in order to gather, collate, refine, and record all available information about the mine threat, its location, and extent.”[13] The General Survey - Level One is conducted “to collect information on the general locations of suspected or mined areas.”[14] This is an appropriate point for application of wide-area detection technology, as mentioned in the Copenhagen Conference. The UN standards only address a labor-intensive, non-technical approach using a minimum of two personnel on the ground.

On September 19, 1996, a Department of Defense report was published “to provide the information required to support FY 98 budget input for an enhanced program for landmine detection, including surface and shallow buried unexploded ordnance.”[15] The report categorizes five areas of concern for detection technology, including Land Countermine (including Battlefield Ordnance), Humanitarian Demining, Explosive Ordnance Disposal (including Battlefield Unexploded Ordnance), Active Range Clearance, and UXO Remediation. The report specifically addresses wide-area detection technologies in connection with verification of an Anti-Personnel Landmine Control Program/Ban (APLCP/B) and in connection with humanitarian demining programs.[16] In Appendix C of the DoD report, Section C.7 addresses two wide-area technology programs (Micropower Impulse Radar and Mapping/Wide Area Detection) supporting an anti-personnel landmine ban and humanitarian demining. Nonetheless, wide-area detection is not reflected in the programmatic summaries of technologies recommended for continuance or enhancement in the report.

The March 1997 "Report to Congress - Unexploded Ordnance Clearance"[17] does contain at least three requirements that appear to be oriented to the wide-area detection of either UXO or mines. Furthermore, at least one requirement is to identify non-contaminated areas, in addition to mined or UXO-contaminated areas. Details of the individual requirements, such as survey rates, are not contained in the report and none of them is connected to an APL ban or control regime.

On September 23, 1996, the U.S. Army Communications and Electronics Command (CECOM), Night Vision and Electronic Sensors Directorate (NVESD) at Fort Belvoir released a Broad Agency Announcement.[18] The announcement, "Humanitarian Demining Technologies for the Detection and Clearance of Landmines," describes a $23-45 million program from Fiscal Years 1997 through 1999. The Night Vision and Electronic Sensors Directorate "seeks to build a balanced program for the development of practical technologies for locating and clearing minefields and for detecting, marking, and destroying landmines." The announcement outlines six categories for technology development and demonstration, one of which is "Wide Area Detection Technologies." Potential developers are advised to include the following characteristics in any wide-area detection system:[19]

- Airborne/ground-based platform;
- Determines the presence or absence of mined areas;
- Offers significant potential to increase the safety of individual deminers at substantially reduced costs;
- Must be capable of accurately detecting and delineating the boundaries of mined areas containing anti-personnel and anti-tank landmines (as well as);
- Capable of locating and plotting individual landmine or landmine cluster locations using Differential Global Positioning System (DGPS) or similar technology; and,
- Capable of generating information that is rapidly transferable to a ground station for storing detected landmine locations.

One U.S. Army-sponsored large-area airborne survey program has been under development for several years. ASTAMIDS is a tactical countermine system intended primarily to support offensive operations. It will fly on an unmanned tactical platform, imposing weight, space, and power constraints on the detector package. Its requirements include performing "real time" data processing, locating 80-90% of the minefields it overflies, and finding minefield boundaries within 150 meters of their actual location. Logistical and survivability goals are comparable to other sophisticated military equipment operating in a hostile environment. It is significant that the objective of ASTAMIDS is to find minefields that contain both ATL and APL; the task of confirming the absence or presence of only APL, as in the verification of an APL ban, would be considerably more difficult.

The ASTAMIDS requirements are suitable for a military application, but requirements for humanitarian demining detection and for monitoring an APL ban are slightly different. First, the environment in which the detection/monitoring system operates would be different from a combat situation—generally, relative political stability would exist and a non-hostile environment would be expected. Second, time would be a constraint, but only in the respect the system must be faster than current interview methods alone. Finally, the detection system for monitoring an APL ban or for humanitarian demining would need to be far more effective than its military counterpart. The system would need to provide either a complete survey of a region or country, or yield baseline information to identify cleared areas and permit in-depth contact surveys or identification and monitoring of mined and suspect areas.

The "United States Department of Defense Humanitarian Demining Program Strategic Plan," of September 30, 1994, contains guidance on the development of demining materiel.[20] In Paragraph 2.4.3, Goal 3, the plan states that one of the objectives of the program is to "establish a materiel acquisition program to field equipment that can assist host nations in detecting and clearing landmines." The plan also notes, "Consider and pursue, if appropriate, a high technology solution that is well advanced of existing equipment."

Given these considerations, therefore, requirements for both wide-area humanitarian APL detection and monitoring an APL ban might include the following:

- Capable of conducting wide-area survey (find minefields instead of individual landmines);
- Equal or exceed present method of on-the-ground interviews;
- Locate minefields accurately within 50 meters;
- Probability of detection ($P_d$) approaching 100% and equal for all types and sizes of minefields;
- False alarm rates (FAR) approaching zero;
- Total time required to detect minefield expressed in weeks, not months or years;
- Multiple sensors are acceptable to enhance detection probability and, if required, to enable operability in all soil, weather/climatic, vegetation and terrain conditions;
- System(s) must be capable of operating in all the climates and terrain found in Africa and Southeast Asia; systems can be configured for a specific climatic or terrain condition;
- Acquisition and operational costs must be quantified to determine operational effectiveness in comparison with other current and proposed wide-area detection methods;
- Does not need to be hardened like a military system but must be rugged enough to withstand environments in host nations;
- High technology acceptable; does not need to be an indigenous capability
- Provides minefield boundaries on map media and a means to acquire the boundaries on the ground for marking;
- "Real time" processing of sensor data not required; and,
- Effects on the host nation environment must be identified.

### 1.8.2 Marking.

Detection of anti-personnel landmines is only useful for humanitarian demining and APL ban compliance monitoring if the information collected in a standoff platform can be accurately relayed to and reliably used by deminers working on the ground. For example, a minefield detected by an airborne ground-penetrating radar must be reacquired on the ground in order to emplace warning signs and to begin the detection and demining of individual landmines. As an interim step, maps would be produced showing the locations of minefields for subsequent use in either demining or verification applications.

Global Positioning System technology, both in its U.S. military version and commercial versions, is well-suited for this task. The requirement to integrate this technology into a wide-area detection system is an engineering task rather than a research and development task.

The Open Skies Data Annotation, Recording, and Mapping System (DARMS), developed by DSWA for implementation of the Open Skies Treaty, may offer some promise in such efforts. DARMS integrates and records aircraft position and navigation data with the data recorded by the Open Skies sensors. It can also provide maps that indicate the route flown by the aircraft, the location at which sensor images were recorded, and the expected sensor footprint, as well as assist in planning the optimum route of flight based on the capability of the sensors and the desired coverage. Although by design the Open Skies system may not provide the accuracy required for the wide-area APL detection mission, many of the same functions must be performed.

Requirements for marking in humanitarian demining and for verification and monitoring under an APL ban might include the following:

- Record minefield detection data on maps for use by all levels involved in the effort, from the national authority down to teams on the ground;
- Technology required for production of maps should be comparable to and compatible with standoff detection technology;
- After standoff detection, acquire minefield boundaries and individual landmine locations on the ground without placing people at risk;
- Develop minefield boundary markers which have no intrinsic value in the host nation yet clearly identify the location of minefields;
- Minefield and individual landmine markers should not present a hazard to emplace or cause an increase in landmine sensitivity;
- Minefield markers should last 1-3 years once emplaced and be replaceable when required and removable when areas are cleared;
- Minefield/landmine markers should be reusable; and,
- Develop a method to mark planimetric "grids" on the ground to control clearance teams after minefield boundaries have been marked; system should be removable, renewable, and reusable.

#### 1.8.3 Neutralization.

Neutralization activities are not applicable to APL compliance monitoring. Requirements for APL neutralization in humanitarian demining operations, however, need to be far more stringent than for military operations. For instance, whereas military operations requirements do include environmental remediation, all components of exploded and unexploded APL must be removed in humanitarian operations so that the formerly mined land can be turned to safe, productive use. Therefore, neutralization requirements in humanitarian operations might include:

- No residual signature;
- No adverse environmental impact;
- Neutralize or remove landmines without collateral damage to personnel or property;
- Self-contained power source;
- Cost $5 or less per mine; and,
- Deminer controls all steps in operational sequence.

#### 1.8.4 Proofing.

Proofing is not applicable to APL compliance monitoring. Proofing for humanitarian demining is essentially identical to detection; the objective is to verify clearance has been performed with an accuracy of 99.6% (U.N. Standard).

### 1.8.5 Protection.

Requirements for protection of vehicles and personnel in humanitarian demining and any ground portions of compliance monitoring operations are similar to those used in military operations and might include the following:

- Vehicle protection:
  - Adaptable to vehicles in host state;
  - Protect occupants from 12 kilogram blast beneath any wheel and front center of vehicle;
  - Low cost - no more than 25 percent of vehicle cost;
  - Removable, repairable and remountable by indigenous personnel; and,
  - Operator-level preventive maintenance checks and services at the same level of complexity as the host vehicle.

- Personnel protection:
  - Protect eyes, hearing and vital organs from effects of a landmine, or equivalent, when exploded at a distance of two feet;
  - Protect feet from effects of a M-14 landmine, or equivalent, when exploded underneath the foot; and,
  - Protect legs, top of feet and groin from the effects of a landmine, or equivalent, when exploded at a distance of 18 inches.

## 1.9 WIDE-AREA DETECTION FOCUS.

In researching the technology requirements discussed in the previous pages for the five tasks associated with demining (detection, marking, neutralization, proofing, and protection), significant RDT&E programs were discovered that are currently underway. Most of these programs focus on detecting APL as point targets and, by association, in proofing the results of individual mine removal. Additionally, there are many other RDT&E programs currently underway investigating technologies that address the requirements for APL marking, neutralization, and protection of personnel involved in the demining operations.

One area, however, in which significant work remains to be accomplished is in developing technology solutions to address the humanitarian demining and arms control compliance monitoring tasks for wide-area detection (WAD) of APL. The only major WAD program - the U.S. Army ASTAMIDS effort - is designed primarily to support the detection of minefields during combat operations. As discussed previously, the WAD requirements for humanitarian demining and for treaty compliance monitoring efforts are considerably different from the requirements for military operations.

A more effective capability to conduct wide-area detection of APL is of vital importance for humanitarian and treaty compliance purposes. Current methods of wide-area detection, including surveys and interviews, are inadequate and inconsistent. Applying technology to the challenges of wide-area detection can help countries plagued by APL—usually less-developed countries—to rapidly turn land previously deemed off-limits to agricultural or commercial development toward productive social and economic ends. In fact, pending ratification of the Amended Protocol II to the CCW, the U.S. has taken on legal obligations to facilitate the exchange of equipment, material, and technological information, and to provide assistance for mine clearance to states. Providing assistance in the wide-area detection of landmines would be a significant contribution to enabling more efficient clearing.

Finally, wide-area detection technologies offer the promise of helping to monitor compliance with restrictive bans on APL use. In this capacity, APL wide-area detection falls within the purview and interest of, and is being addressed in detail by, the Defense Special Weapons Agency (DSWA) Arms Control Technology Program to assess potential DoD requirements and mission needs and to manage the development of technologies needed for the verification and implementation of and compliance with arms control agreements. Such requirements are confirmed in guidance published annually by the Office of the Under Secretary of Defense (Acquisition and Technology) (OUSD(A&T)).

The "Program Guidance and Requirements and Mission Needs Summary," published by the Arms Control Implementation and Compliance Office, OUSD(A&T) on April 12, 1996, seeks technology assessments in support of the CCW and APL Control Program objectives and measures. Some specific verification/compliance and implementation interests in surveying and assessing wide-area APL detection technologies include:

- <u>Verification/Compliance:</u> As indicated in President Clinton's May 1996 decision regarding APL and the President's January 1997 announcement on the initiation of negotiations in the Conference on Disarmament (CD), the U.S. will aggressively pursue an agreement to ban the use, production, stockpiling, and transfer of APL. In his September 1997 statement, following efforts to commence consideration of APL in three sessions of the CD, President Clinton stressed that the U.S. will redouble its efforts to reach agreement on an APL ban in the Conference during 1998. Difficulties in monitoring and verifying compliance with a ban on production, stockpiling, and transfer, however, are quickly apparent. APL are too small, transportable, and easily hidden (e.g., in ammunition storage depots). There are few unique opportunities to employ WAD technologies to find APL during any of these activities.

  In a ban on APL *use*, however, wide-area detection technologies could be of significant value in monitoring States Parties' compliance, in helping to ensure both that new minefields are not established and that existing minefields are not enlarged. WAD technologies could also be of significant benefit in helping to determine whether old minefields have been removed, as potentially required under elimination provisions of an APL ban treaty. Used on an aerial platform, wide-area detection technologies might also be more acceptable than on-site inspection to the states that are now blocking inclusion of verification and compliance measures in the CCW.

- <u>Implementation:</u> The new Amended Protocol II of the CCW, to which the U.S. is a signatory, states, "*Each High Contracting Party undertakes to facilitate....the fullest possible exchange of equipment, material and scientific and technological information concerning the implementation of this Protocol and means of mine clearance.*" Further, "*Each High Contracting Party in a position to do so shall provide* ***assistance for mine clearance****....*" As discussed earlier, participants at the July 1996 U.N. International Conference on Mine Clearance Technology held in Denmark underscored their strong interest in assistance that includes a wide-area detection capability.

## 1.10 THE ASSESSMENT.

The remainder of this assessment consequently focuses on the wide-area detection requirements previously discussed. As cited earlier, this effort involves a survey of literature and of government and industry data, and features an assessment, based on available information, of the technologies and their related systems offering the potential to fully or partially answer the postulated WAD requirements; see

Sections 2 and 3 of this report. Those systems deemed most promising and most applicable to WAD were the subjects of more in-depth, follow-on research, described in Section 5, that included extensive background data collection, personal interviews, and on-site visits to research and production facilities. A review was also made of data fusion techniques and their potential contribution, as discussed in Section 4.2. Additionally, techniques or systems employed in disciplines not commonly associated with the military, such as narcotics interdiction or civil engineering, were surveyed for possible application to WAD; these are discussed in Section 6. Finally, all point target detection and demining information uncovered during the initial research phase of the technology survey is included in a separate appendix to this report.

SECTION 1

ENDNOTES

[1] “National Defense Authorization Act for Fiscal Year 1995, Conference Report to Accompany S.2182,” Report 103-701, GPO, Washington, DC, page 565.

[2] Briefing on the “1995 Humanitarian Demining Technologies Development Program” presented at HRA Humanitarian Demining Program Review and Workshop by Harry N. Hambric, 7 November 1995.

[3] DoD Solicitation DAAB12-95-BAA1, dated 9 December 1994.

[4] Extracted from Enclosure 5 to NVESD Memorandum, Subject: Minutes of the 18-19 Jan 95 Humanitarian Demining and Military Operations Other Than War (OOTW) Workshop, dated January 27, 1995.

[5] This list was downloaded on August 28, 1996 from the "Humanitarian Demining Website" operated by ASD(SO/LIC).

[6] “Countermine Modernization Strategy,” U.S. Army Engineer School, Fort Leonard Wood, MO, July 1997.

[7] Memorandum, Headquarters United States Army Training and Doctrine Command, ATCD-MM, Dated 8 August 1995, Subject: Operational Requirements Document (ORD) for the Handheld Standoff Mine Detector System (HSTAMIDS).

[8] “An Enhanced Program for Detection of Landmines.” DoD Report (originating office not shown), 19 September 1996.

[9] Memorandum, Headquarters United States Army Training and Doctrine Command, ATCD-MM, Dated 29 July 1996, Subject: Operational Requirements Document (ORD) for the Ground Standoff Mine Detector System (GSTAMIDS).

[10] July 1996 Program Overview Briefing, Project Manager for the Mines, Countermine, and Demolitions Program

[11] “Living in a Minefield: An MSF Report on the Mine Problem in Afghanistan,” by Doctors Without Borders/Medicins Sans Frontieres (MSF), May 1997, pg. 5.

[12] “International Standards for Humanitarian Mine Clearance Operations,” United Nations; Overview section. Taken from internet site http://www.un.org/Depts/Landmine/UNDocs/standard/html on 27 March 1997.

[13] Ibid, Section 3.4.

[14] Ibid, Section 3.41.

[15] "An Enhanced Program for Detection of Landmines", 19 September 1996. (Originating office not shown in report.)

[16] Ibid, pg. 6 and 7.

[17] "Report to Congress - Unexploded Ordnance Clearance: A Coordinated Approach to Requirements and Technology Development," Office of the Under Secretary of Defense (Acquisition and Technology), 25 March 1997.

[18] DoD Solicitation DAAB12-97-BAA1.

[19] Ibid, pg. 2.

[20] See "Humanitarian Demining Operations Equipment Planning Guide," U.S. Department of Defense Humanitarian Demining Program, prepared by the Office of the Assistant Secretary of Defense for Special Operations and Low Intensity Conflict, 1 August 1997.

# SECTION 2

# DETECTION TECHNOLOGIES

## 2.1 INTRODUCTION.

For the purposes of this report, the following definitions are utilized:

> TECHNOLOGIES are the approaches by which principles of physics are exploited to achieve tasks (for example, wide-area detection), including ground-penetrating radar, ultrasound, mechanical action (for example, application of force), electromagnetic induction, etc.
>
> SYSTEMS are the devices that incorporate one or more technologies to achieve tasks.

Requirements for a wide-area humanitarian detection and compliance monitoring system were proposed in Section 1 of this report. In a standard RDT&E program made up of several development phases, these objective requirements would form the basis for exit criteria to be met at the end of each discrete development phase. But in order to compare and evaluate ongoing research and development efforts in varying stages of development and maturity, it is necessary to develop a less restrictive and more inclusive number of criteria. The following, more general, criteria are offered for selecting a technology that may have applicability for wide-area detection (WAD):

- The technology does not require direct contact with, nor movement through, mined or suspect areas;

- Standoff distance for applying the technology is at least equal to the lethal radius of the largest suspect explosive device;

- Use of the technology from stand-off ranges and/or at wide-area search rates should not pose a risk to humans on the ground or in a search vehicle; this includes risks from landmine detonation and from the technology itself (for instance, eye hazards from lasers, strong electromagnetic fields from electromagnetic induction devices, and radiation hazard from radioactive sources);

- The technology is compatible with the search platform—for example, it does not weigh too much for the search vehicle, is not too large, functions at wide-area search rates, and has power requirements within the platform's capabilities;

- Technology transfer does not create a security risk; this includes the potential security risk posed by instrument readouts or data generation. However, this concern may be mitigated by the control of the technology during WAD operations by U.S. personnel or restricting maintenance of aspects of the technology to U.S. contractors. High technology equipment may be used as long as it meets this criterion; and,

- The technology allows the reacquisition of targets for use in marking.

A literature search was performed to identify any and all levels of RDT&E programs that specifically address landmine detection. This search resulted in over 150 documents that to some degree discuss the development of APL detection systems or their underlying technologies. By sorting the different systems identified and discussed in the literature by type, the following APL detection technologies were identified:

- Magnetometry/Gradiometry
- Radar, including
  - Ultra-wideband
  - Ground Penetrating
- Infrared
- Millimeter Wave
- Visible/Ultraviolet light
- LIDAR
- Acoustic, including
  - Seismic
  - Sonar
  - Ultrasonic
- Electromagnetic Induction
- Chemical/Biological, including
  - Dogs/Animals
  - Gas Chromatography
  - Mass Spectroscopy
  - Bioluminescence
- Mechanical, including
  - Probers
  - Rollers
- Nuclear, including
  - Photon Backscatter
  - Thermal Neutron Analysis
  - X-ray
  - Nuclear Magnetic Resonance

This list was further sorted by applying the more general wide-area detection technology selection criteria discussed above. As a result, the following technologies were removed from further consideration for wide-area detection applications:

- Chemical/Biological - Aerial sample collection is rendered ineffective by wind, diminished trace emissivity of old landmines, localized spreading of trace elements over time, and sampling obstruction due to ground cover. Moreover, this approach requires the characterization and recording of all sought chemicals' signatures. Included in this are gas chromatography and mass spectroscopy techniques;[1]

- Mechanical - Requires direct contact with the ground and involves seeking out the explosives, a somewhat slow and always dangerous approach; and,

- Nuclear - Radiation source can present a hazard to users in the immediate vicinity, even for point source systems. The source would not be powerful enough to illuminate a wide area unless it were very large, which would pose that much greater a radiation hazard. These approaches are also very time consuming.[2]

Findings from the preliminary analysis were initially inconclusive regarding acoustic/ultrasonic technologies and the use of free-ranging dogs or other animals. Further assessment, however, also ruled out these technologies as not viable to the wide-area detection task.

- Acoustic[3] - Difficulty in distinguishing between natural and man-made objects since they produce similar acoustic returns; this would result in an very high false alarm rate. Also, a large device is needed to generate the acoustic waves. Moreover, acoustic waves experience difficulties due to refraction when passing between different density media (for example, from air to ground or between different temperature strata in the atmosphere), rendering inaccuracies in imaging. This would pose a particular difficulty with buried landmines.

- Free-ranging dogs - Since explosives continuously give off distinct vapors or pheromones, those vapors can be detected by the acute olfactory capabilities of dogs.[4] Although free-ranging dogs working with their handlers can navigate terrain that vehicles or aircraft may not be able to penetrate, such as heavily vegetated areas, rough terrain areas, or urban areas, using dogs or any other animals is very costly in terms of training the animals and their human handlers. The speed of detection and removal is still somewhat slow, with work periods as short as 30 minutes. Additionally, this method of detection remains effective for a relatively short time period, since explosives give off decreasing amounts of vapor over time.

Based on this sorting, the remaining technologies were selected for further assessment. Those technologies found potentially suitable for wide-area detection are described below. Accompanying each description are discussions of the strengths and weaknesses of the technology, in general and as it pertains to wide-area detection. Basic technology descriptions were derived from a Jet Propulsion Laboratory report entitled, "Sensor Technology Assessment for Ordnance and Explosive Waste Detection and Location,"[5] written for the U.S. Army Corps of Engineers and Yuma Proving Ground, and supported by other references.

Table 2-1 on the next page provides a synopsis of the wide-area detection potential of the selected technologies. The table presents an assessment of each technology's possible applicability to the WAD mission. It is not intended to indicate the current or projected operational potential.

## 2.2 MAGNETOMETERS/GRADIOMETERS.

***Description:*** Ferrous metal objects subjected to the earth's uniform primary magnetic field generate smaller secondary magnetic fields. A magnetometer can be used to detect the perturbations caused by buried and surface objects containing ferrous metal. The non-linear magnetic characteristics of a magnetometer's sensing coil (also called a saturable-core, saturable-inductor, saturated-core reactor, or peaking strip) are exploited to determine the strength and position of the source of magnetic field fluctuations. The strength of an object's secondary magnetic field varies with its mass and with the strength of the earth's ambient magnetic field where it resides and diminishes as $1/r^3$ (or $1/r^4$ for gradiometers, discussed below), where $r$ is the distance between the object and the sensor. The sensor must be sensitive enough to distinguish secondary magnetic field strengths ranging from fractions of one gamma to tens of gamma for detected metallic objects against the earth's ambient background magnetic field strength, which ranges from about 35,000 gamma at the equator to about 60,000 gamma at the poles. The strength of the background magnetic field is also affected by soil composition (clay content generates additional secondary fields).[6]

Gradiometers employ a pair of magnetometers separated by a set distance to measure differences in magnetic moments (i.e., magnetic field volume times intensity) between the two sensors. Since secondary magnetic field strength varies with the distance between an object and the sensor, the separate magnetometers will sense different field strengths in the presence of ferrous metallic objects. State-of-the-art gradiometers can measure along three coordinates, allowing greater accuracy in pinpointing the location of metallic objects.

**Table 2-1. Synopsis of wide-area detection potential of selected technologies.**

| TECHNOLOGY | Applicability for Monitoring Ban and Detecting Minefield Changes | Role in Humanitarian Demining Operations (HDO) and UXO Detection |
|---|---|---|
| Magnetometers/Gradiometers | Marginal; only good for close-in (point) detection | HDO - Marginal; effective for ferrous metal; problems with plastic and non-ferrous<br>UXO - Good point-source detection of ferrous metal |
| Radar | Good; potential for wide-area applications if resolution vs penetration, detection probability vs false alarm rate, clutter issues are solved | HDO and UXO - Good; possible problems with plastic in some soils |
| Infrared Sensors | Marginal to Good; potential for wide-area detection with limited obscurants; affected by duration of soil disturbance thermal effects | HDO and UXO - Marginal to Good, depending on system resolution |
| Millimeter Wave Sensors | Marginal to Good; potential for wide-area detection at slow scanning rate | HDO and UXO - Marginal to Good, depending on ability to discriminate mines from surroundings |
| Visible Light Sensors | Poor to Marginal; might detect surface changes, but easily obstructed, cannot see buried items | HDO and UXO - Poor; cannot detect buried items |
| Light Detection and Ranging (LIDAR) | Marginal; potential use for unobscured (surface) and recently emplaced mines | HDO and UXO - Marginal; can only detect surface-laid objects and the potential presence of recently placed explosives |
| Electromagnetic Induction | Marginal; only good for point detection of metal mines | HDO - Marginal; effective for metal mines, problems with plastic<br>UXO - Good point source metal detection |

Different types of magnetometers exist that could be used alone or in a gradiometer configuration, each employing different approaches to detecting fluctuations in magnetic fields. These include:

- Proton precession magnetometer - The proton precession magnetometer operates on the principle that the protons in an unbalanced polar molecule (such as water, kerosene, or other hydrocarbon fluids) will have different natural (Larmor) frequencies of precession when subjected to different magnetic fields. This approach yields an absolute measurement of the magnetic field intensity with a sensitivity that varies with sampling time; 1 second samples can yield 0.05 gamma, while 0.1 second samples can yield 0.5 gamma. However, this technology is susceptible to noise from AC power sources, transmission lines, and electric storm activity. A recent enhancement to this technology, called the Overhauser effect, employs an added fluid rich in electrons to enhance the polarization effect 5000-fold, thereby maximizing resolution, diminishing power demands, and greatly decreasing response time to near-real-time.

- Optically pumped atomic magnetometer (also called atomic magnetometer or cesium vapor magnetometer) - In this technology, an external circularity-polarized illumination (pumping) light source excites the atoms of a specific gas vapor from their ground state to multiple levels of excitation. The atoms thus aligned precess about an ambient magnetic field at an appropriate Larmor frequency determined by the atomic structure. This atomic resonance corresponds to the ambient magnetic field strength. This approach yields order-of-magnitude improvements in sensitivity over the proton precession magnetometer, faster (essentially continuous) sampling rates, and a very wide dynamic sensing range (0.001 to 60,000 gamma). However, this technology requires that the sensor be aligned fairly well in the ambient magnetic field.

- Fluxgate magnetometer - When the soft magnetic material core of a solid-state fluxgate sensor is subjected to a periodic excitation field, ambient magnetic fields induce a DC flux proportional to the measured field intensity and at the second and higher harmonics of the excitation frequency. This technology results in a rugged device of low energy consumption. However, the magnetic and mechanical stability of the sensor, which can be affected by such factors as temperature changes, affects its performance. While this technology can be employed as a single-axis detector, it can also be configured as a three-axis fluxgate to provide simultaneous determinations of distance and direction to an object.

- Superconducting quantum interference device (SQUID) magnetometer - By using a superconducting coil that has been cooled with liquid helium to 4.2 $^{o}$K, this technology results in the greatest signal-to-noise ratio of any existing magnetometers. Of three SQUID technologies available - direct current (DC), radio-frequency (RF), and microwave, DC is the most sensitive. Such devices have been used in biomagnetism to measure brain waves. This technology may be sensitive enough to detect buried ferrous metal ordnance from the air.

- Fiber-optic magnetometer - This technology uses a fiber Mach-Zehnder interferometer to measure the strain induced in a transducing material by a magnetic field. A field-dependent phase shift proportional to the field intensity is induced in the interferometer and detected and measured by an output detector. By using three interferometers in this manner, a ferrous metal object can be located along the three coordinate axes. This technology provides a sensitivity of about 0.1 gamma. As an electrically passive system, this technology is not affected by electromagnetic interference. Moreover, negligible line losses over even very long fiber optic lines allows significant standoff distances between an operator and the sensor head.

- Electron tunneling magnetometer - In this technology, a magnetic field causes a bar magnet attached to a microscopically small, electrically biased electrode tip to deflect, closing a gap and allowing a varied amount of quantum mechanical tunneling of electrons across a narrow barrier. The resultant tunneling current, which is measured, is proportional to the deflection and thus to the magnetic field strength. This technology allows a sensitivity of as little as 0.001 gamma in measuring magnetic fields.

***Strengths:*** Devices that employ these technologies are generally well developed, cost-effective, and reasonably easy to use. They can measure very fine degrees of variations in a magnetic field and, when properly arrayed, can be used to accurately locate ferrous metal objects. In addition, gradiometers are much more sensitive than single magnetometers, affording more than four times the sensing range. Moreover, they are "passive" devices that emit no signal of their own and thus do not run the risk of detonating munitions sensitive to radio frequencies.

***Limitations:*** These technologies can only be used to detect objects that contain ferrous metal. Moreover, they cannot discriminate landmines from shrapnel, spent ordinance, and other metallic clutter, and soil content can cause additional and confusing secondary magnetic fields; all of this can result in a large number of false-positives. In addition, the ability to sense objects decreases rapidly with the distance between the sensor and the object. Successful use of these technologies also depends on the environment in which they are used and the experience level of the operator.

## 2.3 RADAR.

***Description:*** Radar technology, as applied to the interrogation of solid materials, typically involves the transmission of short radio and microwave ($10^2$ to $3x10^3$ MHZ) radiation pulses from an antenna into the ground and measuring the time for reflections to return to the same antenna. Reflections occur at the boundaries between materials of different dielectric constants that are orthogonal to the incident radiation. Several variations of radar technology are currently employed or envisioned to detect obscured or buried landmines. These variations typically differ in the operating frequency and spread (bandwidth) of the electromagnetic spectrum they employ, the type of signal they emit, the way its return is interpreted, and the type of antenna they use. Ground Penetrating Radar (GPR) systems typically emit into the ground an electromagnetic wave covering a large frequency band, the broadest of which is called Ultra-wideband (UWB). GPR systems then measure reflections of this wave caused by the dielectric variations on top of and within soil that may indicate the presence of surface or buried objects. In most GPR approaches, the antenna is moved about, enabling an operator to construct an image representing a vertical slice of the soil.

The two most prominent radar types are real-aperture radar and synthetic aperture radar (SAR). Real-aperture radar makes use of the largest possible antenna to produce a narrow angular beam width in the azimuth direction, while SAR employs a smaller antenna to transmit a broad beam. SAR, in turn, relies upon extensive signal data processing to increase the effective size of the antenna.[7]

In a technology called micropower impulse radar (MIR), developed by Lawrence Livermore National Laboratory, the timing of the reflected returns from very-short-pulsed radar emissions, sensed by the

MIR's rapidly opening and closing electronic "gates," provides information about the distance and location of the buried, reflecting object(s).[8] This technology requires fairly close proximity of the radar source to the object, depending on its material.

One emerging GPR approach searches for and isolates a third harmonic component in the reflected radio or microwave emission, which may specifically indicate the presence of hard metallic joints found only on man-made objects; this technology is called harmonic radar. Another approach, called an interferometric impulse radar, identifies landmines within interference patterns generated from GPR reflections off of underground objects. The resolution of this approach - approximately one-third the wavelength in the soil under measurement - is likely to be more coarse than the individual landmines sought. One further new technique is called stepped frequency modulation, or stepped FM. Stepped FM overlays images taken at multiple, regularly-spaced frequencies that probe different ground depths at different resolutions. This approach employs extensive computer processing for data fusion to generate high quality information and images.

GPR systems deployed from an airborne platform require higher transmitter power and receiver sensitivity than ground-based systems, and, being aboard a fast-moving platform, must be able to process data at much higher collection rates for real-time landmine detection. Airborne systems also must reconcile technical trade-offs between ground penetration capability, image resolution, and antenna size limits.

***Strengths:*** GPR is a mature technology and has been used for over 15 years in civil engineering, geology, and archeology. GPR systems can create images of surface or buried objects with higher resolution than such technologies as electromagnetic induction or magnetometry, which in their simpler forms just sense the presence of objects. Additionally, GPR systems can detect non-metallic objects, as long as their dielectric characteristics are sufficiently different from the surrounding media. Using GPR on an airborne platform alleviates problems associated with ground-based platforms: movement through thick vegetation is no longer an obstacle, operation may occur at higher speeds, and broader surface imaging can be performed.

The signal employed in MIR technology is also too low in power to affect detected ordnance, and it is not expected to affect, nor be affected by, other nearby electronics. Moreover, this technology is being developed to provide two-dimensional and three-dimensional images to enhance detection accuracy.

***Limitations:*** GPR is slow to use, and interpreting radar returns often requires extensive expertise unless an adequate degree of automated data processing can be achieved to compensate for different operator skill levels. Automated data processing, in turn, would require extensively characterizing the widest possible range of radar images to be interpreted and discriminated. In addition, underground materials can affect radar penetration depth, which can range from hundreds of meters in the case of low electrical conductivity soils, to tens of meters in granite, to a fraction of a meter in high-clay-content soil. Even a small amount of clay minerals greatly degrades GPR performance, as can the presence of fired bricks, which contain clay. Moisture also changes the dielectric constant of different materials through which the radar may pass, thereby affecting its effectiveness and accuracy. Moreover, image resolution and penetration depth are functions of frequency, type of radar mode, and polarizations. For instance, if the radar frequency is reduced, depth of penetration increases but resolution decreases.

For wide-area detection systems, airborne platforms typically require higher transmitter power and receiver sensitivity, as well as a higher data processing rate for real-time capability. MIR may suffer from its low-range limitations, particularly given its very low power; it is currently only envisioned being deployed in a hand-held or vehicle-mounted configuration. Harmonic radar requires the presence of hard metallic edges on the landmines, which may not always occur. Harmonic radar is projected as best suited to detecting clusters of large metallic objects, as opposed to individual landmines. Moreover, metallic clutter may present hard joints and edges that cause false alarms. The resolution of interferometric impulse radar appears too large to detect individual landmines, while stepped-FM radar may require excessively high data collection and processing rates to provide real-time (or reasonably fast turn-around) imagery.

Concerns also exist about whether airborne GPR, in general, can be used in conjunction with Global Positioning System (GPS) navigational tools, since interference between the two have been shown to exist when GPR is transmitting at frequencies similar to that at which GPS operates.[9] Due to the bandwidths used by most GPR systems, interference with or from TV and FM signals can be problematic.

## 2.4 INFRARED.

***Description:*** The burial of a landmine results in the disturbance of the ground's surface as well as the introduction of a mass whose thermal characteristics may differ from surrounding soils. Environmental factors such as soil type, precipitation, and the heating effects of the sun also affect the thermal signatures. All of these factors create varying types and levels of photon emittance or reflectance by the soil and the landmine. These photons are detected and differentiated by an imaging infrared detector array. Landmine detection through infrared imagery exploits these traits by detecting the difference in temperature and/or reflectivity between a landmine and its surrounding soil[10] or between disturbed soil or vegetation and adjacent, undisturbed terrain. Viewing in the thermal infrared wavelength, IR sensors thereby reveal landmines by discerning those thermal signatures in the soil surface above buried landmines.[11]

IR spectrometers detect and analyze IR radiation across a range of wavelengths. Multispectral spectrometry employs measurements at selected wavelengths, while hyperspectral spectrometry involves contiguous, relatively narrow bandwidth measurements taken across a wide spectral range. Using the analysis of multiple spectral bands, data of different wavelengths can be compared and correlated for greater target discrimination.[12] Mid-wave IR (MWIR) and long-wave IR (LWIR) sensing may address the surface texture differences in disturbed versus undisturbed surface soil (although this affect typically only lasts up to several weeks), while the spectral signature of disturbed soil may be detected for a period of weeks to months in multiple IR spectral regions. The localized, lower spectral reflectance of fine, clinging particles brought to the surface through digging is noticeable in the LWIR portion of the thermal IR spectrum, indicating a potential mine burial site, while reflection IR (in the near and short-wave IR region) can be used to detect spectral differences associated with the composition of unearthed minerals. These approaches are in addition to temperature detection techniques, wherein the difference in temperature between a buried mine and its surrounding soil (caused by their differing thermal masses and conductivities), and between recently disturbed soil and the undisturbed soil around it, are exploited for mine detection.[13]

Sensors exist or are under development that function in the near- through thermal-IR wavelengths. Fast Fourier transform (FFT) and other spectral discriminator techniques are being developed to aid in more rapid and accurate imaging with very high resolution. In addition, IR sensors lend themselves to image fusion and are being employed in concert with other spectral technologies.

Active infrared systems provide images in reflected intensity and relative range.[14] One approach utilizes active, near-infrared (NIR) scanners that detect and assess the reflection of NIR radiation off of object surfaces. This radiation is typically provided by a visible light source or a laser. The polarization of radiation reflected from the target object versus the ground may also be compared to better discriminate the target.

***Strengths:*** The temperature anomaly of a buried mine is typically very long-lasting, while the spectral signature of disturbed soil may last up to several months. Infrared detectors readily lend themselves to production in line and area array configurations, which permit the creation of relatively compact and rugged imagers. Infrared detectors also work in a wide array of soil types and are effective at detecting non-metallic objects. This technique has been used successfully by the U.S. Army to detect buried ordnance minefields from airborne platforms in a single pass over a field, and therefore represents a relatively mature technology.

NIR laser scanners can provide high spatial resolution, including possible 3-D images; day or night use; no shadow-producing image clutter; and the coverage of a large area in a side- or down-looking configuration.

***Limitations:*** Infrared detection that depends on a contrast in temperature between the soil and the landmine or between disturbed and undisturbed soil can be affected by such factors as weather conditions (including solar radiation, cloud cover, ambient temperature, wind speed, and surface moisture), time of day, background environment, and size and composition of the landmine. Increased soil moisture may shift the thermal characteristics of the soil to improve the detection of non-metal mines but reduce the detectability of metal mines.[15] Detecting mines by sensing their temperature difference from surroundings may suffer from target/clutter discrimination problems. Moreover, infrared sensors have difficulty detecting objects buried deeply; the IR signature of landmines buried more than 15 cm may be too difficult to detect.[16]

There are also limits to the duration and effectiveness of soil disturbance spectral and textural signatures. Weathering will diminish these signatures, while other sources of soil disturbance can lead to false detections. Variations in soil composition, temperature, wind conditions, shade, vegetation, and terrain, and the presence of subsurface water and buried rocks all subject IR systems to higher false alarm rates. Intense rain, snow, or fog can also render most IR sensors useless at long ranges.

NIR laser scanning can suffer from reflectivity variations across the object's surface and may present problems when employed on a moving platform. This approach also requires data collection on the reflectance of landmines.

## 2.5 MILLIMETER WAVE RADIOMETRY.

***Description:*** Millimeter wave (MMW) radiometry detects and locates sources of MMW-range emissions that differ from, and stand out against, ambient background emissions[17]. One approach exploits the property that objects differing in tempature from their surroundings will present different MMW-range signatures. Surface-based or superficially buried metallic objects, with heat capacities that differ from the ground around them, will heat and cool at different rates over the period of a day and therefore present different MMW-band signatures that are strongest when the temperature differences are greatest. Operating on the same principal as infrared (IR) radiometry that detects IR signatures, MMW radiometry then detects and differentiates the MMW signatures to discern the presence and location of the metallic objects. A temperature map is made of an area of terrain by collecting the thermal signatures in the relevant wavelength (in this case, about $10^{-3}$ meters), and objects of different temperatures will stand out against the more uniform background emissivity.[18]

Another approach exploits the difference between the emissivity and reflectivity of soils (high and low, respectively) versus that of metal (low and high, respectively). Soil radiation is therefore dependent mostly on its temperature, regardless of ambient (i.e., solar) radiation, while radiation from metallic objects is mostly reflected, not emitted. MMW radiometry measures this contrast to detect metal objects. Laboratory experiments have been able to locate metallic objects buried in up to three inches of dry sand.[19]

MMW radiometry devices require an array of channels that are scanned over time to compile single point intensities into an image. Systems with multiple apertures as well as multiple channels are being investigated to improve overall spatial resolution and image generation time. MMW radiometry performs, on average, about as well as IR radiometry, with the comparative strengths and limitations (described below) effectively canceling out.

***Strengths:*** MMW emissions, with their longer wavelength, are not very attenuated by clouds or rain, which strongly absorb IR. MMW radiometry thus lends itself to foul weather applications.

***Limitations:*** MMW emissions are typically much weaker than IR emissions; at about 120 degrees Fahrenheit, IR emissions are nine orders of magnitude greater than MMW emissions. As a result, MMW signatures take longer to collect and process and require larger-aperture collection devices (and aperture size directly affects spatial resolution). Moreover, non-uniform background conditions may make it difficult to isolate specific objects using MMW radiometry.

## 2.6 VISIBLE LIGHT.

***Description:*** Visible light detection involves capturing light waves of visible wavelengths using an image-forming optical system, such as a camera. A visual imager gathers a beam of light from an object point and transforms it into a beam that converges toward or diverges from other points on a focal plane, thereby producing an image. Powerful photographic systems are readily available commercially and have been employed on aerial platforms for many decades.

While conventional (film-based) photographic equipment may be used, electronic formats are more useful for data fusion and analysis purposes. Electronic imagers act as transducers that convert the photon energy received into an electrical output where the signal is electronically processed and displayed. Some of the most popular electronic photo equipment, known as charge-coupled devices (CCDs), are small, lightweight, and effective. CCDs control the movement of signal electrons by the application of electric fields--this shifts a group of signal electrons from input to output without distorting the signal itself. CCDs have very fine resolution (a few centimeters) and are considered state-of-the-art. Another, more recent form of electronic imager is the active pixel sensor (APS), which could rival the CCD in performance but first problems with charge transfer must be overcome. If accomplished, APS may potentially lend itself to better electronic data handling and integration.

Finally, spectral filters may also be employed to discriminate the unique visible spectrum signatures of paints used on landmines.

***Strengths:*** Visible imagery, a passive approach that does not present a detonation risk, affords high spacial resolution and texture in real time. Visible light sensors are helpful in identifying extraneous findings of other sensor types, such as infrared or radar sensors. Visible light sensors can also be used in standoff platforms, such as aircraft or even satellites, to detect both metallic and nonmetallic landmines. Visible light sensors represent a relatively mature technology that are often compact and low in cost relative to other wavelength sensor types.

***Limitations:*** Visible wavelength light, which does not transmit as well as other wavelengths, can fairly easily be blocked by camouflage or foliage. Visible light sensors are useful only on flat land with little vegetation. By definition, these sensors are less effective in poor lighting conditions (unless assisted by auxiliary lighting or light amplification devices) and virtually useless in foggy or cloudy climatic conditions. Additionally, visible imaging sensors cannot detect objects beneath the surface.

The identification of landmines by their unique visible spectra signatures would also require the collection of those many possible signatures, as well as the data processing necessary to discern landmine signatures from those of other objects.

## 2.7 LIDAR.

***Description:*** Analogous to radar (radio detection and ranging), LIDAR (light detection and ranging) is an optical technology that works in the visible and infrared regions of the electromagnetic spectrum.[20] Such instruments send out pulses of coherent radiation, a fraction of which are reflected back by surface-laid objects. LIDAR sensors measure both the traveling time of the reflected pulses and the difference between transmitted and reflected energy, which are used to calculate the distance to the target and its general reflectivity or absorption.

If the LIDAR receiving equipment is comprised of an array of detectors, the received signal can be angularly resolved as an image of the object from which the return signal was reflected--commonly referred to as 2-D imaging LIDAR. If the receiving imager is switched on (gated) at discrete intervals after transmission of the initial pulse (a technique used to improve the signal-to-noise ratio, wherein the receiver is turned on at a time when a return from a known object is expected), then the images received at each interval can be reconstructed into a 3-D LIDAR picture. By employing polarimetric LIDAR systems that detect polarization changes in the backscattered energy obtained after illuminating the target with linearly polarized light, surface landmines can be detected due to their smooth qualities in comparison to the surrounding natural backgrounds.

Subsurface landmines also can be indirectly detected by sensing for specific chemical vapors or liquids escaping from emplaced munitions. Laser-induced fluorescence (LIF) LIDAR radiates at a frequency that would affect the chemical(s) sought; the excited molecules in turn fluoresce back at typically a lower frequency, which is detected by the LIDAR system. Spectral “fingerprinting” can be performed using line spectra LIDAR to identify specific chemicals. Other 3-D LIDAR variations include Raman LIDAR, in which the system’s receiver is tuned to detect one or more suspect chemicals within a mixture; aerosol measurement LIDAR, which detects simple airborne gases by their backscatter of a fixed-frequency laser;

and differential absorption LIDAR (called DIAL), in which the difference in absorption of nearly identical wavelength radiation provides information on the molecular density of a gas.

***Strengths:*** LIDAR is capable not only of detecting both metallic and nonmetallic objects in a wide variety of climatic conditions during the day or night, but also of creating images of such objects. LIDAR can be used at substantial standoff distances or by wheeled or tracked vehicles in locations deemed inaccessible . Additionally, LIDAR involves the use of extremely sensitive sensor equipment to provide near-real-time data, high spatial resolution, and rapid spatial survey in three dimensions. LIDAR has also been used successfully to measure gas composition, temperature, pressure, and wind velocity.

***Limitations:*** LIDAR is not capable of imaging below the ground surface. Also, 2-D LIDAR does not work well in moderately to highly vegetated areas. LIDAR may cost substantially more than other sensor technologies. The low return signal strength of Raman LIDAR limits its range, sensitivity, and daylight operation. Aerosol measurement LIDAR cannot distinguish between aerosol density and aerosol size. Other 3-D LIDAR systems that seek airborne gases may not readily detect older landmines whose outgasing of volatile (explosive signature) chemicals has greatly diminished over time.

## 2.8 ELECTROMAGNETIC INDUCTION.

***Description:*** In sensors that employ electromagnetic inductance, the presence of a metallic object causes a change in the inductance of a nearby coil, which in turn causes a change in the natural frequency of a tuned circuit that an operator can hear or see on a meter. Typically, a sensor employs two coils: a transmitter coil and a receiver coil. A magnetic field is generated by passing a low-frequency electromagnetic pulse wave from the transmitter coil, causing eddy currents in the buried or surface-laid metallic object.[21] After the transmitted pulse ends, a secondary magnetic field caused by those decaying eddy currents induces a voltage in the receiver coil.

By employing in one sensor several electromagnetic induction coils at different orientations (e.g., coplanar and coaxial) and emitting at different frequencies, fairly well defined signatures can be derived that correspond to the shapes of buried objects. However, this resolution capability diminishes with distance. Airborne sensors have been developed and employed to detect a change in ground conductance of a wide area, indicating the potential presence of very large collections of buried ordnance or other metallic objects, but not individual items. One such electromagnetic induction system has been used on a rotary wing platform to measure a nuclear waste burial site by sensing differences between the conductivity of solid granite areas, where materials cannot be buried, and granite sand, where materials are buried.

***Strengths:*** Electromagnetic induction is a mature, proven technology. An electromagnetic induction sensor is able to detect the presence of any type of metallic object.

***Limitations:*** Electromagnetic induction sensors, even those employing multiple sensors and frequencies, cannot readily discriminate between different types of metallic objects, nor can they readily resolve the shape or size of deeper objects, when deployed on an aerial platform. This can result in a high false alarm rate in areas with metallic clutter. In addition, the secondary magnetic field induced in buried metallic objects diminishes rapidly with distance, making stand-off detection difficult. Moreover, the “active” nature of this technology - applying an electromagnetic field - may cause detonations if the field strength near the landmine is too strong, although this has not proven to be too great a problem to date.

SECTION 2

ENDNOTES

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# SECTION 3

# SYSTEMS

## 3.1 INTRODUCTION.

As stated earlier, systems are the devices that incorporate one or more technologies to achieve tasks. Numerous systems were identified in this report that employ technologies discussed in Section 2 above. Some of these systems are fully developed and have entered the prototype production stage. Most systems, however, are only in the developmental stage. Below, individual systems that may be applicable to wide-area detection are outlined and assessed. Those projects in a developmental stage or for which information was very limited are grouped together by technology and discussed under the various General Programs headings. Systems selected by DSWA for further investigation in a follow-on to this literature survey (entitled Assessment 2 - see Section 5 of this report) are so indicated.

## 3.2 GEONEX AERODAT, INC. MAGNETOMETER/GRADIOMETER AND EMI SENSOR.

In a 1994 demonstration to evaluate the state of the art in unexploded detection and remediation technology, a combination of two cesium vapor magnetometers in a gradiometer configuration and an electromagnetic induction sensor, each produced by Geonex Aerodat, Inc., were suspended from an airborne (helicopter) platform and tested over an 80-acre landmine detection test site at Jefferson Proving Ground, Indiana.[1] The tests concluded that this system's ability to detect the buried landmines from the aerial platform were virtually nonexistent.

**Assessment:** These tests were performed in 1994 and may not be indicative of the most recent technological capabilities.

## 3.3 GROUND PENETRATING RADAR SYSTEMS - GENERAL PROGRAMS.

Researchers at the U.S. Army Communications Electronics Command, Night Vision and Electronic Sensors Directorate at Fort Belvoir are examining the use of surface penetrating radar for ground troops. Israel Aircraft Industries, based in Lod, Israel, is researching similar application of ground penetrating radar to detect both metallic and nonmetallic landmines. ERA Technology, of Letherhead, Britain, has developed a ground penetrating radar system known as SPRscan that is capable of detecting images up to two meters beneath the ground surface. SPRscan is a lightweight, portable system whose application to wide-area detection may be limited.[2]

A report entitled, "Minefield Detection Capabilities for Humanitarian Demining Operations," prepared by GeoDynamics of Torrance, California, rated ground penetrating radar against a number of other landmine detection technologies, concluding that GPR performed best in detecting ferrous, non-ferrous, and non-metal landmines on grassy land, on cleared land, in sandy/loamy soils, on flat or gently sloping land, and in arid or semiarid areas. Ground penetrating radar performed poorly in thick clay soils, areas with high water tables, along saltwater coastlines, and in wet or marshy land. The report also listed a variety of GPR systems, the particular vendor or developer for each system, the developmental status of each system, and the platform employed by each system.[3]

TNO Defence Research of the Netherlands has performed research in vehicle-mounted landmine detection systems involving ground and vegetation penetrating radar. Their efforts showed that back-scattered radiation created by the emission of electromagnetic radiation can be used to detect buried and surface landmines. The amount of backscattered radiation gives the Radar Cross Section (RCS) of the object. The RCS of a landmine reveals the object's size and the material of which the object is constructed. However, it is noted that no single type of radar can detect all landmines under all circumstances. Their research also indicated that since the best imaging radar systems use a high frequency, have a spatial resolution smaller than the landmine size, and are aimed downward at angles perpendicular to the landmine surface, real aperture radar systems should be flown at altitudes below 100m.[4]

Bertrand Gros and Claudio Brushini of EPFL presented a paper at the International Symposium on Measurement and Control in Robotics held in Brussels on 9-11 May 1996. Their research showed that ground penetrating radar has been in use by engineers, geologists, and archeologists for about 15 years. They explained how a wide frequency band provides the best resolution, but also noted that since higher frequencies do not propagate as well, the chosen frequency band is a tradeoff between resolution and penetration depth. The authors cited research programs taking place in Sweden under the "FOA team", which is examining the development of automatic recognition algorithms for landmine detection; at the Lawrence Livermore National Laboratory, which has developed and patented Micropower Impulse Radar; at the European Microwave Signature Laboratory, which has demonstrated good imaging capabilities for surface-laid landmines and landmines buried at shallow depths; and at the Ohio State University, which has detected complex resonances from ground penetrating radar.[5]

In September 1995, the Naval Post Graduate School published a paper written by A.J. Healey and W.T. Webber in which the authors discussed research on landmine detection in a number of technology fields. In discussing ground penetrating radar, Healey and Webber note that microprocessing of signal returns from the target, time of signal flights, phase polarization, amplitude time delay and propagation direction all yield information on target type and location. They also found that such systems are limited by high moisture content in soils, reliance on metallic or air/plastic interfaces which must provide sufficient return for detection, and energy loss at the air/surface interface. Overall, the authors state that soil type is probably the overriding variable in the performance of ground penetrating radar systems.[6]

A report entitled, “Survey of Mine Clearance Technology,” conducted by the United Nations University and the United Nations Department of Humanitarian Affairs, discussed ground penetrating radar as one of the most promising landmine detection technologies currently under development. The survey identified system dynamic range, absolute bandwidth of the receiver signal, range clutter, and spatial clutter as the four most important factors that govern radar performance when applied to landmine detection. Problems cited with ground penetrating radar include: challenges posed by the change in dielectric constant between the air and the ground; data handling; and target recognition. Nevertheless, the survey cites successful work underway in applying ground penetrating radar to landmine detection at the Ohio State University and at the FOA in Sweden.[7]

Research by Erik Johansson and Jeffrey Mast of Lawrence Livermore National Laboratory has focused on a three-dimensional synthetic aperture imaging techniques for evaluating bridge decks and road beds through time-domain focusing of pulse-echo radar data. Their particular radar technique involves not a carrier frequency to transmit signals, but rather an extremely short electromagnetic pulse. As an antenna is moved across a target, the received pulse signals that echo from the target form a hyperbolic arc in space and time. When surveying multiple targets in complex media, the resulting space-time images are difficult to interpret. By using a synthetic aperture focusing technique, the researchers have developed a three-dimensional algorithm that focuses each of the arcs into a single point, thereby forming accurate spatial images of the target.[8]

A draft survey of Landmine Detection Research and Development at the National Laboratories conducted by Capt. Phillip Hezeltine (USAF) of the Field Command Defense Special Weapons Agency and Dan Miller and David Reitzel of the Center for Verification Research in Albuquerque, New Mexico, investigates the technologies available through the National Labs for point or wide-area landmine detection. The authors found that Lawrence Livermore National Laboratory is working to develop: micropower impulse radar to create three-dimensional images of buried ordnance coupled with automatic target recognition; multi-frequency diffraction tomography, which uses a pulse echo radar to detect subsurface objects; and, synthetic aperture time-domain focusing, which uses a time domain algorithm rather than frequency domain.[9]

Papers presented at the 1995 meeting in Orlando, Florida of the International Society for Optical Engineering revealed a variety of research projects and program on applying ground penetrating radar to the detection of landmines. The paper entitled, "Developmental GPR Mine Detection Technology Known as Balanced Bridge," by Kelly Sherbondy of Fort Belvoir and David Lang of GDE Systems in San Diego, outlined a new balanced bridge detection concept that involves a multi-octave bandwidth, incorporation of audio and visual presentations of digitally processed signals, a broadband printed circuit board antenna, RF transmit and receive components, and a digital signal processor. Author Martin Fritzshe of Daimler-Benz presented a paper entitled, "Detection of Buried Land Mines Using Ground-Penetrating Radar," that provided a discussion of the underlying principles and limitations of ground penetrating techniques, the advantages of three-dimensional versus two-dimensional image processing techniques, and factors that determine the resolution of ground penetrating radar. The paper, "Detection of Surface and Buried Mines with an UHF Airborne SAR," by Theodore Grosch, Check Lee, and Eileen Adams of MIT, Chi Tran, Francois Koening, and Kwok Tom of the Army Research Lab, and Roger Vickers of SRI International, details the field tests of the SRI FOLPEN II synthetic aperture radar used on the ground and in the air in detecting metallic and nonmetallic landmines on the surface and buried at three different depths below the surface. Their paper also shows the image-clarifying results of a new radio frequency interference rejection algorithm.[10]

A paper by Vernon Joynt, entitled "Detection of Hard to Find Mines," presented at the International Conference on Mine Clearance Technology held in Denmark on 2-4 July 1996, outlined the limitations of ground penetrating radar systems used in Namibia and Angola due to high false alarm rates.[11]

### 3.4 BATTELLE APL DETECTOR (GPR).

In a 1994 demonstration to evaluate the state of the art in unexploded detection and remediation technology, two ground penetrating radar systems were tested, one an experimental system developed by Battelle in cooperation with Ohio State University and the other a system cited only as a Battelle initiative.[12] The first system, a surface-towed GPR using a rope/tape/odometer arrangement for navigation, was subjected to ground-based testing over a 40-acre landmine detection test site at Jefferson Proving Ground, Indiana, of which only 2.3 acres were actually searched in a five-day period.

The second system was a stepped-chirp radar (which moves to a certain frequency, takes numerous data readings at a certain frequency, then moves on to another frequency) functioning in the 50-750 MHZ range, with antennas pointing 15 degrees below horizontal. This preliminary prototype system, although designed for aerial platform mounting, was mounted to the arm of a cherry-picker (an extendable-boom ground vehicle) driving down a road and tested at 40-60 foot altitudes. These tests were performed over a separate 80-acre detection test site, also at Jefferson Proving Ground, although effectively only 29 acres were searched. It was cited that the test configuration —in essence, mounted on a boom—may have limited the system's effective range to about 500 feet.

The tests found that the ground-based system performed relatively poorly, producing significant false declarations per ordnance item detected. The tests further found that the platform-mounted system's ability to detect the buried test landmines were virtually nonexistent.

It was noted that the high clay-content soil conditions at Jefferson Proving Ground limited the performance of both systems.

**Assessment:** These tests were performed in 1994 and may not be indicative of the most recent technological capabilities. Moreover, the wet, clay soil conditions cited in the report should not remove this technology from further consideration for use in other environments, e.g., dry, sandy conditions, where GPR functions better.

## 3.5 JAYCOR VEHICLE-MOUNTED STANDOFF LANDMINE DETECTION SYSTEM.

JAYCOR, of San Diego, California, has developed a proof-of-principle standoff landmine detection system funded through the U.S. Army Communications and Electronics Command at Ft. Belvoir.[13] The JAYCOR system employs ground penetrating radar and is designed to detect surface and buried landmines from distances of up to 100 feet. A conceptual system, weighing about 200 pounds, has been designed for use atop a Jeep.

The JAYCOR system uses a stepped continuous wave signal directed and received through three horn antennas to detect, locate, and identify targets. In a variety of field tests, JAYCOR's system was successfully demonstrated.

Preliminary design specifications are for a system that weighs 50 lb. with a volume of two cubic feet, and an antenna that weighs 20 lb. with a volume of six cubic feet. The system would be designed for functioning at 25 kph. It would have a locational accuracy of one foot nominal, with a best case performance of four inches. Power is indicated as 100 watts.

**Assessment.** While the maximum speed of the JAYCOR proof-of-principle system is limited to 5km/hour for effective data acquisition, this application may be adaptable into an airborne platform. Planned system improvements also call for combining infrared scanning technologies with the current system, which may improve system accuracy.

Further investigation was made of this system in Assessment 2; see Section 5 of this report.

## 3.6 GDE SYSTEMS ADVANCED TECHNOLOGIES.

GDE Systems of San Diego, California, has engaged in research to prove the viability of a landmine detection system that combines ground penetrating radar with infrared imaging technologies to provide the user with a standoff detection capability.[14] They indicate, however, that this sort of system would require more controlled detection operations, such as favorable weather conditions and specific time-of-day operation. Collected data can then be merged with terrain data and operational imagery through digital image processing techniques.

**Assessment:** There are limitations on the usefulness of this application given the stringent environmental factors necessary for successful operation. However, in treaty compliance and humanitarian demining scenarios, time constraints are of less concern, permitting operational flexibility to work around temporary environmental conditions such as rain, snow, and darkness. Overall, this application appears to need further development.

## 3.7 REMOTE DETECTION VEHICLE.

The QSine Corporation of Canada is working on a contract from the Canadian government to design the Remote Detection Vehicle for use in advanced landmine detection operations.[15] The $230,000 effort, which was funded in March 1996, was expected to be completed by March 1997 (the status of which had not been cleared for public release as of the publication date of this report)[16] and is designed to establish the contractor base necessary to provide an off-the-shelf supplier of vehicles and subsystems. Canada's National Defence will facilitate the design of the vehicle, while QSine's work will be improved with the efforts of the prime contractor, Computing Devices Canada of Calgary, who will provide the installation kits for various sensor technologies.

Using induction, ground penetrating radar and infrared detection sensors, the Remote Detection Vehicle system is designed to detect metallic, low-metallic and non-metallic landmines. These sensors will be mounted on an unmanned vehicle.

**Assessment:** As a ground-based vehicle, this application may be of little use in wide-area detection. Moreover, it is also unclear whether or how data from these sensors will be fused.

## 3.8 ALLIEDSIGNAL MINEFIELD RECONNAISSANCE AND DETECTOR (MIRADOR) SYSTEM.

AlliedSignal Kirtland Operations (KO) has improved upon a commercially-developed detection system called MIRADOR by implementing known pattern extraction algorithms on the system's short-pulse radar and its metal detector, as well as improving its electrical and mechanical subsystems.[17] The system, initially developed for the U.S. Army Program Manager - Mines, Countermines, and Demolitions (PM-MCD) and tested in 1989, in more recent tests detected 85 percent of all buried and surface-emplaced metallic and non-metallic objects.

KO scientists are now developing a second-generation MIRADOR system called the Improved Ground Mobile Mine Detection Testbed (IGMMDT), which employs infrared, GPR, metal detectors, and visible cameras. The sensors' data is combined using neural network techniques to generate composite images of detected objects. This approach is intended to help discriminate landmines and other sought items from ground clutter and refuse.

**Assessment**: It is unclear from the literature how successful this new approach has been, nor whether this device and its improvements can be applied to wide-area detection. One of the sensors on the IGMMDT - the metal detector - may not have the range necessary for stand-off applications, although in a "data-fused" sensor suite, it may prove useful or necessary. This approach also relies on active detection technologies that might detonate landmines sensitive to electromagnetic radiation, although this risk is minor. Moreover, this system appears to require characterizations of all sought items (i.e., all different types of landmines) to adequately "recognize" one when it is encountered.

Further investigation was made of MIRADOR in Assessment 2; see Section 5 of this report.

## 3.9 ULTRA-WIDEBAND RADAR SYSTEMS - GENERAL PROGRAMS.

James D. Taylor, of Gainesville, Florida, has edited a book entitled Introduction to Ultra-Wideband Radar Systems, designed as an introductory reference sources covering technology and concepts of ultra-wideband (UWB) radar systems. Taylor's book is aimed primarily at those who design, evaluate, analyze, or use UWB technology for any of a number of applications. The various authors in Taylor's compilation stress theory and hardware in the developing field of UWB technology and present basic principles and concepts to help those designing UWB systems. Section headings include Ultra-Wideband Radar Overview, Transmitters, Ultra-Wideband Antenna Technology, Direct Radiating Systems, and Propagation and Energy Transfer.[18]

Vexcel, of Colorado, has recently been awarded a contract by the Defense Advanced Research Projects Agency to work on a new airborne landmine detection system developed by the Environmental Research Institute of Michigan. This system employs ultra wideband radar technology to provide polarimetric, sub-meter resolution synthetic aperture radar imagery.[19]

In its report on "Localisation and Identification of Anti-Personnel Mines," the European Commission's (EC) Joint Research Centre (JRC) discussed ultra wideband radars under the general heading of Surface Penetrating Radar systems. The European Microwave Signature Laboratory (EMSL), located in Ispra, Italy, has developed a new imaging algorithm for application to data collected through ultra wideband radar sensors. The report notes that, although several European countries are working on surface penetrating radars that may employ ultra wideband technologies, Sweden is the only European Union member state with a national program envisaging application of these technologies to the localization and classification of landmines. The report goes on to call for a coordinated European research and development program in this area.[20] Further investigation was made of the EC JRC's RDT&E activities in Assessment 2; see Section 5 of this report.

A draft survey of Landmine Detection Research and Development at the National Laboratories conducted by Capt. Phillip Hezeltine (USAF) of the Field Command Defense Special Weapons Agency and Dan Miller and David Reitzel of the Center for Verification Research in Albuquerque, New Mexico, investigates the technologies available through the National Labs for point or wide-area landmine detection. The authors found that Pacific Northwest Laboratory is developing a UWB Radar Holographic Imaging system to detect buried targets. The technique employed by this system creates a three-dimensional image of both metallic and nonmetallic objects.[21]

Papers presented at the 1995 meeting in Orlando, Florida of the International Society for Optical Engineering revealed a variety of research projects and programs on applying ultra wideband radar technology to the detection of landmines. A paper entitled, "SAR Imaging of Minelike Targets over Ultrawide Bandwidths," by Dennis Bleger, Carl Frost, and Steven Scarborough of the MIT Lincoln Lab, and Karl Kappra and Keith Sturgess of the Army Research Lab, outlines the effectiveness of a ground-based detection and imaging system.[22]

## 3.10 LAWRENCE LIVERMORE NATIONAL LABORATORY MICROPOWER IMPULSE RADAR.

Lawrence Livermore National Laboratory (LLNL) has put extensive effort into the development of its proprietary micropower impulse radar (MIR), a very-low-power, highly compact, high-resolution radar and imaging device.[23] MIR employs an ultra-wide bandwidth at about 1 GHz frequency with a 1 Ghz frequency spread and a pulse repetition frequency of about 1 MHZ. Its 100 picosecond rise time yields about a 2 cm range resolution in typical soils. MIR's microwave pulse is "dithered" (or randomized) which ensures that no interference occurs between separate MIR units. LLNL has also developed data processing algorithms that generate 2-D and 3-D images from the radar's data, aiding in distinguishing buried objects.

MIR was developed in 1993 as an evolution of government-sponsored work on radar combined with technology developed for LLNL's transient digitizer. Additional work was funded by DSWA as of February 1996.

While currently still in the developmental stage for APL detection, the underlying technology of MIR has been functionally applied to or commercialized for detectors that find reinforcing steel bars in concrete; fluid level sensors; and motion detectors in alarm systems. Evaluations of MIR potential as a landmine detector, begun within the past two years, have focussed on MIR as a point source detector and imager, however, not as a wide-area detection system.

Earlier LLNL work with a high-power radar-based landmine detector aids in current MIR development efforts. That previous system, whose power exceeds MIR's by several orders of magnitude, had a stand-off range of only about 9 meters. Current developmental efforts using MIR have focussed on a design range of only 0.5 meters (in look-down mode) to 3.0 meters (in look-ahead mode). LLNL indicates it has been able to render 3-D images of known plastic and metallic landmine mock-ups buried in 5-10 cm of moist soil and in up to 30 cm or more of dry soil. LLNL efforts indicate that, while 2-D imaging may be used to detect a specific buried object, 3-D imaging may be necessary to distinguish it from other buried objects. However, the scan-geometry (MIR signature) of each object sought must first be entered into the MIR computer for comparison and identification purposes.

LLNL envisions deploying an array of MIR units in a look-ahead configuration for roads or look-down configuration for off-road (highly cluttered) areas, mounted to a remotely-controlled ground vehicle. The field of view, about 2-4 $m^2$, is scanned so that a 2-D aperture is synthesized, and data is transmitted back to a remote data-processing and control location. The computer (a 486-level PC), employing diffraction tomography methods, takes under 10 seconds to reconstruct an image, and requires information to be entered previously about the media (air and ground), scan timing, and scan geometry. Outstanding issues the developers seek to address include clutter reduction, enhanced resolution and contrast, electromagnetic attenuation by different media, multiple scattering, shadowing, dispersion, real-time operation, and full 3-D imaging speed.

**Assessment:** This system is anticipated to be very inexpensive. However, it does not currently offer an adequate degree of stand-off detection capability. The greatest stand-off range it has been tested at is 3 meters (although one recent report indicates a range in air of 10 meters), whereas aerial or other wide-area detection platforms will require much greater range capabilities. Moreover, while this application may in the near-term provide detection and imaging capabilities for point-source detection of known landmines, extensive efforts may be necessary to characterize the various targets sought (i.e., buried and surface landmines) required by the associated data processing computer.

Further investigation was made of MIR in Assessment 2; see Section 5 of this report.

## 3.11 ARMY RESEARCH LABORATORY BOOM-MOUNTED, ULTRA-WIDEBAND RADAR SYSTEM.

In 1994, the U.S. Army Research Lab, located in Adelphi, Maryland, started a 6.2-level, Army-funded program to develop an ultra wideband radar system for the detection and location of near surface landmines. This system consists of sensors used from a 150-foot high mobile imaging platform to resolve small targets in three dimensions. ARL's system may, however, be employed on helicopter platforms, thereby augmenting its wide-area capability.

The Army Research Lab's system is based on an impulse transmitter developed by Power Spectra, Inc., and was shown in field tests to be capable of detecting small, low-metal content objects. The detection system includes a high-speed data processor and an imaging digitizer.

**Assessment:** Questions remain regarding problems posed by different types of soil, moisture content of soils, and electronic interference. Additionally, an airborne platform has yet to be selected.

Further investigation was made of this system in Assessment 2; see Section 5 of this report.

## 3.12 TIME DOMAIN SYSTEMS, INC., ULTRA-WIDEBAND RADAR SYSTEM.

Time Domain Systems, Inc. of Huntsville, Alabama, is developing a technology called ultra-wideband tomography for the detection of both metallic and non-metallic buried ordnance.[24] The radar technology involved in this application employs Gaussian monocycles to construct a three-dimensional picture out of a series of two-dimensional images. This application also depends upon the development and use of an ideal antenna that is small, flat, inexpensive, and capable of operating at low voltage.

Because of its high bandwidth, the monocycle is capable of resolving very small objects. Additionally, ultra-wideband tomography operates at a very low electromagnetic frequency, providing maximum resolution with little loss due to absorption by the Earth. Ultra wideband transmissions also do not interfere with military or commercial radars and radios.

Time Domain Systems, a private research and development firm, has been involved in development of ultra-wideband radar technology since 1987. The company cites initial tests in 1991 as being “favorable” and they are now seeking investors or strategic partners to complete construction of a prototype. A company called Tomographic Technologies, Inc. ($T^3I$) was also formed to commercialize landmine and unexploded ordnance detection technologies.

**Assessment:** The cited initial testing of this system was done in 1991 and the system may therefore not reflect the most advanced technology. The literature gives no indication of the speed at which this application may be operated.

Further investigation was made of this system in Assessment 2; see Section 5 of this report.

## 3.13 SRI INTERNATIONAL AERIAL DETECTION SYSTEMS.

SRI International, of Menlo Park, California, has designed, built, and tested prototypes through Defense Advanced Research Projects Agency-sponsored projects aimed at developing foliage-penetrating synthetic aperture radar. In a 1994 demonstration to evaluate the state of the art in unexploded detection and remediation technology, three ground penetrating radar systems developed by SRI International were tested from either ground-based or aerial platforms.[25] SRI's radar system uses ultra-wide bandwidths to form continuous, real-time scrolling images that are integrated with Global Positioning System information and then recorded onto optical disks. The systems included a trailer-mounted arrangement looking forward and down (30 degrees from horizontal) with a range of about 100 feet; a GPR unit employing a synthetic aperture algorithm, tested from a fixed-wing aerial platform and using GPS for navigation; and a test of an ultra wideband, bistatic GPR tested from a rotary wing aerial platform. Operational altitude for SRI's aerial platform systems ranged between 1,000 and 10,000 feet about ground level.

Tests of the ground-based system were performed over a 40-acre landmine detection test site at Jefferson Proving Ground, Indiana, of which the system only succeeded in searching 13 acres in a one-week period. Tests of the aerial platform-based systems were performed over a separate 80-acre detection test site, also at Jefferson Proving Ground. It was noted that the wet, clay soil conditions at Jefferson Proving Ground limited the performance of the aerial platform-based systems.

The tests found that the ground-based system performed relatively poorly, producing significant false declarations per ordnance item detected. The tests further found that the aerial platform-mounted systems' ability to detect the buried test landmines were virtually nonexistent.

**Assessment:** These tests were performed in 1994 and may not be indicative of the most recent technological capabilities. Moreover, the wet, clay soil conditions cited in the report should not remove this technology from further consideration for use in other environments, such as dry, sandy conditions, where GPR functions better.

Further investigation was made of SRI's aerial systems in Assessment 2; see Section 5 of this report.

## 3.14 AIRBORNE ENVIRONMENTAL SURVEYS.

In a 1994 demonstration to evaluate the state of the art in unexploded ordnance detection and remediation technology, two wideband frequency-modulated radars centered on 500 MHz and 3 GHz, respectively, were combined with a forward-looking infrared (FLIR) 2000F imager and tested from an airborne (helicopter) platform.[26] The tests were performed over an 80-acre landmine detection test site at Jefferson Proving Ground, Indiana. The tests concluded that this combined system's ability to detect the buried test landmines from the aerial platform were virtually nonexistent. Source literature provided insufficient information for a more detailed system description.

**Assessment:** These tests were performed in 1994 and may not be indicative of the most recent technological capabilities.

## 3.15 INFRARED IMAGING SYSTEMS - GENERAL PROGRAMS.

Defence Research Establishment Suffield (DRES) - Investigations were made of the ability to detect over 24 hours the temperature contrasts between plain ground cover and the ground above buried anti-tank landmines using a camera sensitive to long wave infrared (8-12 pm) and temperature differences of 0.1 $^{o}$C.

The camera was deployed 15 meters from the observed ground surface. They found that the average maximum apparent thermal contrast due to the landmine alone, 2 $^{o}$C, disappears for landmines buried deeper than 8 cm. The thermal effect of disturbed (versus undisturbed) soil above a landmine provides about a 50 percent increase in the thermal contrast (i.e., increasing to 3 $^{o}$C), regardless of burial depth. DRES finds this result promising for the detection of anti-tank landmines buried in compacted soil using a passive IR imager, although a high false-alarm rate and the uncertain duration of the disturbed soil's thermal effect cause certain concern. They also conclude this approach may be effective where the soil surface can be viewed directly, is irradiated uniformly, and is uniformly compacted, and the landmine was buried fairly recently. This might occur on dirt roads regularly inspected for landmines.[27]

According to the European Commission's Joint Research Centre, an English laboratory found that thermal contrasts between the ground and sought objects, particularly man-made objects, may be enhanced using polarization-sensitive infrared sensors. The Centre states that the resolution range of these sensors should rival that of optical instruments. However, the Centre also states that several national programs find that IR radiation cannot penetrate foliage nor the ground and thus conclude that IR sensors are only effective on surface-laid landmines.[28]

The U.S. Army's Special Operations Command Central (SOCCENT) Demining Headquarters performed a survey of demining technologies that might be used to assist demining efforts in Eritria. Their survey found about 12 different infrared technology-related development efforts underway throughout the U.S. However, they state that not enough information was available at the time of the survey to assess the performance of the systems.[29]

A report by the TNO Defense Research in the Hague assesses a variety of landmine detection systems and recommends, for a ground vehicle-mounted deployment configuration, the use of passive and active, mid-, and long-wave IR imaging in a data-fusion suite with other sensor technologies (near-wave IR is dealt with under the visual technologies portion of this report). IR line scanning (IRLS) systems (which scan transversely to a line of travel to form a 2-D image) and forward-looking IR (FLIR) systems (which adds a vertical scan component to an IRLS to generate 3-D images) comprise the two IR technology formats assessed, including both active (retro-reflective) and passive systems. It is stated that passive systems with focal plane arrays (an array of multiple detectors in a single unit) may detect landmines of about 5 cm in diameter (both surface-laid and buried, as implied by the reference source) at a range of 500 meters. However, clutter greatly reduces detection accuracy. Active systems suffer less from clutter, but instead experience problems with image speckle, a strong variation in reflection across an object's surface. The report recommends further research into the use of IR-based sensors, particularly in conjunction with other sensor types.[30]

In a survey of sensor technologies performed by EPFL-LAMI DeTec of Switzerland, a short-range, point-source detection system developed by Martin Marietta Technologies for the U.S. Army was identified. This system uses a commercial 8-12 meter IR sensor and neural networks that recognize patterns segmented from the image. It is reported that this system achieves 90 percent target detection at current stages of development (the report was presented in May of 1996). No further information was provided on this system. This report also briefly cites two competing anti-tank landmine detection systems to be evaluated in the first half of 1996, one by EG&G that employs a combination of GPR, IR cameras, and metal detectors, and the other by Geo-Centers, which employs a combination of GPR and IR cameras.[31]

The Department of Mechanical Engineering at the Naval Postgraduate School performed a review of land-based munition detection sensor development and a survey of commercially available equipment, although none of the equipment cited performed IR sensing. The study notes that the soil disturbed when a landmine is emplaced will have a different moisture content than surrounding soils, which in turn results in a different infrared signature that is most apparent during periods of greatest air/soil temperature differential. It also notes that IR systems are particularly well suited to airborne platforms and integrate well with intelligent data processing, but they are also limited by weather conditions and the overall moisture content of the soil.[32]

Among the abstracts of reports on landmine detection-related technologies cited in a 1995 publication of SPIE proceedings, two describe IR-based systems. One summarizes research done by Defence Research Establishment Suffield (DRES), Canada, on an airborne, long-wave IR (LWIR) system that uses an intensity-modulated $CO_2$ laser, which provides images in reflected intensity and relative range of surface-laid landmines. It indicates that tests have achieved a 2 mm range resolution, with no image speckle noise but potential problems have been encountered when the system is used on inclined surfaces. The other abstract addresses a passive system that employs multispectral IR signal polarimetry. By evaluating the relative plane of polarization of reflected shorter-wavelength solar radiation versus longer-wavelength emitted radiation, a scene could be examined and spatially compared using suitable algorithms to determine the presence of man-made features such as surface-laid or exposed landmines. This approach was investigated by Aerodyne Research, Inc., and Boeing Defense and Space Group, who performed modeling analyses and field measurements.[33]

## 3.16 U.S. ARMY AIRBORNE STANDOFF MINEFIELD DETECTION SYSTEM (ASTAMIDS).

The Joint Countermine Advanced Concept Technology Demonstration (JCM ACTD) program, involving efforts by the U.S. Navy, the U.S. Marine Corps, and the U.S. Army, is funding work on the Airborne Standoff Minefield Detection System (ASTAMIDS).[34] As a joint-service program, JCM ACTD is tasked with ensuring the connectivity and integration of systems demonstration, balancing workloads, and avoiding duplication.

ASTAMIDS consists of an infrared sensor or infrared and laser sensor package, combined with a minefield detection algorithm and processor, and fielded on an unmanned aerial vehicle (UAV). The system is designed to provide near real-time minefield information in either day or night operations. ASTAMIDS seeks to detect and identify the boundaries of patterned and scattered anti-tank minefields by using input from an on-board Global Positioning System (GPS).

Some sources estimate that such a detection system should be field-ready within five years.

**Assessment:** Major hurdles in the effort to use airborne sensors to detect landmines include integration of sensors, incorporation of sensors with the selected airframe, selection of the data-processing equipment, and acquisition cost.

Further investigation was made of ASTAMIDS in Assessment 2; see Section 5 of this report.

## 3.17 OILTON INFRARED IMAGER.

In a 1994 demonstration to evaluate the state of the art in unexploded detection and remediation technology, a FLIR 2000 AB infrared imager was mounted to an airborne (helicopter) platform and tested over an 80-acre landmine detection test site at Jefferson Proving Ground, Indiana.[35] The IR images were correlated to visual images simultaneously recorded by a CCD camera and compared to surface landmarks. The tests concluded that this system’s ability to detect the buried test landmines from the aerial platform were virtually nonexistent.

**Assessment:** These tests were performed in 1994 and may not be indicative of the most recent technological capabilities.

### 3.18 MILLIMETER WAVE (MMW) SYSTEMS - GENERAL PROGRAMS.

The European Commission's Joint Research Centre assessed several different types of APL sensors, including those functioning in the MMW band. They note that MMW sensors' resolution is limited by the wavelength sought and the corresponding antenna size. They also recommend using frequencies of 94 to 220 Ghz (3 to 1.25 mm wavelength) to ensure a reasonably fine resolution. Thomson-Thorn Missile Electronics, an English company, is cited as achieving good images of even small objects. However, they also cite the inability of these systems to penetrate the ground and vegetation, so this type of system may only be applied to surface-laid landmines. It is noted that polarimetry will improve the contrast between sensed objects and their surroundings.[36]

Researchers at TRW Space and Electronics Group in California addressed the detection using passive MMW sensors of MMW radiation (at 44Ghz) emitted from an environment containing metal landmines laid on the surface of, or buried in, dry sand. MMW radiation from soil, which has a high emissivity and low reflectivity, depends mostly on its temperature, while MMW radiation from metal, which has a high reflectivity and low emissivity, depends mostly on the presence of ambient radiation. TRW concludes from their research that, using passive MMW sensors under ideal laboratory conditions, metal can be detected when buried up to three inches in dry sand.[37]

### 3.19 SCATTERED MINE DETECTION SYSTEM (COMPACT AIRBORNE SPECTROGRAPHIC IMAGER).

ITRES Research Ltd. reports on a system development effort in which specific data processing algorithms were applied to 16-band hyperspectral images captured from an airborne (helicopter) platform in September 1994 to detect the presence and specific location of landmines in a terrestrial scene. A 16-band hyperspectral compact airborne spectrographic imager was used to capture the 0.5 meter x 0.5 meter pixel resolution images. The resulting data was processed with PCI Easi/Pace image analysis software using spectral unmixing (SU) and linear correlation coefficient (LCC) algorithms developed by the Canadian Defence Research Establishment Suffield (DRES) and ITRES. The combination of the two algorithms yielded highly accurate data on the location of the buried landmines.[38]

**Assessment:** It is unclear whether this application addressed buried, or only surface-laid, landmines. The use of hyperspectral images could include IR, microwave (radar), and other spectra to determine the presence and location of buried objects, but no further information is available. The algorithms used in this application also appear to require the prior characterization of the signatures of all objects sought, which could amount to 750+ signatures.

Further investigation was made of DRES' RDT&E activities in Assessment 2; see Section 5 of this report.

### 3.20 LIDAR - GENERAL PROGRAMS.

In a 1995 report from the European Commission's Joint Research Centre, light detection and ranging - LIDAR - is described as a system that employs coherent light sources (lasers) in the visible and IR wavelengths. From the timing of a laser light reflection the range of an object or its features may be determined; from the strength of the reflection relative to the light source an object's composition may be inferred; and from an analysis of spectral scattering of the returning energy the type of object may be further determined. The article mentions without further detail that research and testing has been done in Germany on the detection of plastic landmines. It also states that it has been proposed that the vibrational behavior of different objects be analyzed using LIDAR for the analytical tool and a heavy ground vehicle to provide a forcing function. However, it is not indicated that research into this approach has been undertaken.[39]

The U.S. Army's Special Operations Command Central (SOCCENT) Demining Headquarters performed a survey of demining technologies that might be used to assist demining efforts in Eritria. Their survey found only one effort that may be applicable to landmine detection, an IR-based LIDAR under development by the Army Corps of Engineers' Waterways Experiment Station. The survey also reports that a MMW-based LIDAR system is being researched by the Army Research Lab. However, neither effort is said to be directly focused on landmine detection.[40]

The potential for airborne surface detection using lasers is indicated in a Naval Postgraduate School report as potentially feasible. However, drawbacks cited include the inability to penetrate soil to a significant depth. No performance information is cited for any research-level or commercially available LIDAR-based systems.[41]

### 3.21 SUPER-CONDUCTING QUANTUM INDUCTION DEVICES (SQUID).

Los Alamos National Laboratory (LANL) has been working on the application of SQUID technology for landmine detection. Their approach involves feeding the background signal back into the SQUID, indicated as then comparing and separating that signal out from the target induction field. This approach is taken to improve the system's signal-to-noise ratio.[42]

**Assessment:** Insufficient data was available at this time to render an accurate assessment. LANL indicates that, with adequate funding, a proof-of-concept demonstration could be ready within one year.

### 3.22 MECHEM EXPLOSIVES AND DRUG DETECTION SYSTEM (MEDDS).

Mechem Division at Denel (Pty.), Ltd., in South Africa, has developed a system in which air samples are taken from ground-based locations that are precisely recorded with GPS.[43] Specially trained explosive-sniffing dogs, working away from the hazardous area, are used to identify which of the vapor concentration tubes contain traces of explosives. Areas associated with the suspicious air samples are then directly swept using conventional landmine location techniques (dogs, electronic sensors, etc.) to pinpoint potential landmines. It is stated that this approach is approximately four times faster than clearance using free-ranging dogs. Mechem claims this approach is 99 percent accurate.[44]

**Assessment:** This approach improves the speeds with which dogs can "inspect" an area and removes them from the immediate hazard in the process. However, it also introduces a ground-based sampling requirement that would be hazardous to human drivers and, even if remotely piloted, may not be able to access all possible locations. Moreover, the air sampling technique could be greatly degraded on windy or extremely cold days, when the vapor pressure of an aged landmine might be too weak to emit an adequate trace.

SECTION 3

ENDNOTES

[1] "Evaluation of Individual Demonstrator Performance at the Unexploded Ordnance Advanced Technology Demonstration Program at Jefferson Proving Ground," DTIC Report, reference number A295074, 30 March 1995.

[2] "Countermine Technologies Flow from Increased Threat," Defense News, July 8-14, 1996.

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[4] Remote Land Minefield Detection: An Overview of Techniques, TNO Defense Research report, September 1994.

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[17] “MIRADOR Minefield Reconnaissance and Detector System,” AlliedSignal Kirtland Operations, 1994.

[18] James D. Taylor, ed., Introduction to Ultra-Wideband Radar Systems, December 1994.

[19] “Land Mines Pose Hazards Worldwide,” press release from Vexcel, taken from internet site at http:\\www.vexcel.com\ tech_feat\ land.mines.html, 1996.

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[25] "Evaluation of Individual Demonstrator Performance at the Unexploded Ordnance Advanced Technology Demonstration Program at Jefferson Proving Ground," DTIC Report, reference number A295074, 30 March 1995.

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[27] "Experimental Evaluation of the Apparent Temperature Contrast Created by Buried Mines as Seen by an IR Imager," Defence Research Establishment Suffield (Canada) Report, November 1994.

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# SECTION 4

# ASSESSMENT 1 FINDINGS

## 4.1 GENERAL.

The literature search upon which Assessment 1 is based yielded a multitude of technologies and systems that might be applicable to wide-area anti-personnel landmine detection. However, no uniform, validated technical requirements for the wide-area landmine detection mission were identified in the literature search. Technical requirements are critical for further research, development, testing and evaluation of wide-area landmine detection technologies and systems. Such requirements will provide developers with specific goals to work toward and a standard against which results can be independently assessed.

The information uncovered through the literature search indicates that, given the limitations inherent in each system, there does not currently exist a single technology or system that is capable of providing a complete solution to wide-area anti-personnel landmine detection. For instance, although radar seems to be the focus of much of the current research and development in APL detection, radar only performs well in a narrow array of soil types. Conversely, infrared sensors work in a wider variety of soil types, but are adversely affected by poor weather conditions and are limited by the time of day when temperature differentials between the soil and a buried landmine are minimal.

## 4.2 DATA FUSION APPROACH.

As a solution to the shortcomings posed by individual technologies or systems, a multiple-technology approach employing data fusion may help to minimize the limitations and leverage the strengths of each technology or system. Data fusion is the combination of sensory data from multiple sensors with relevant information from supporting databases in an attempt to synthesize more informative, accurate, and reliable output information. It may provide improved accuracy and more specific inferences than may be possible with single sensors. Using more than one sensor, even of a single type, affords a statistical advantage through redundant observations of a single feature, while the use of different types of sensors may improve the accuracy with which a feature can be characterized and observed.[1] Such strategies may yield increased probabilities of detection and lower false alarm rates.

In a basic approach, two or more different sensors can be employed individually in scanning an area of terrain to collect two or more sets of data. That data would then be compared or overlaid with one another to provide a more comprehensive understanding of the scanned area and objects therein. Data interpretation for decision making or inference about the presence, characteristics, and identity of a sought target[2] (i.e., a landmine) is then performed by a computer algorithm or human operator. Multiple sensors might be used simultaneously, or in series, with one or more cuing on a suspect item and others used to confirm or deny the find.

In more advanced, “feature-level” data fusion, representative image features are extracted from multiple different sensor observations and combined, or fused, into a single image that is then subjected to pattern recognition algorithms. Decision-level data fusion can also be performed, wherein a preliminary assessment is made at the sensor of an item’s location, characteristics, and identity; the resultant information is then combined.[3] An important consideration in data fusion system development is the selection of a point at which the data flow is to be combined.[4]

Extensive development work has been done in the field of data fusion. According to Moshe Kam, Director of the Data Fusion Laboratory at Drexel University, Philadelphia, PA, the basic structure of algorithms employed in data and sensor fusion is quite uniform, with considerable development already having been done on the underlying mathematics. These algorithms employ fairly generic techniques, which can be migrated from one discipline to another, to aggregate the data provided by the sensors employed. Data fusion relies on the modalities (sensors) used to detect the data. Mr. Kam noted that the way a data fusion algorithm is employed is therefore entirely application-specific.[5]

Several signal processing tools used in data fusion are commercially available, including Interactive Data Language, P-Wave, AtLab, and others.[6] Developers can adapt these software packages as necessary, as well as develop their own software, for their unique individual applications.

## 4.3 TECHNOLOGY SYNERGY APPROACH.

As opposed to using two or more sensors or systems separately, the technology synergy approach involves applying two or more technologies in novel ways. In this approach, two or more technologies are used to produce a new and more informative data set that neither could have produced alone. For example, an ultrasonic wave generator might be focused on an area of ground that is simultaneously interrogated using LIDAR. The ground and any surface features or buried objects excited by the ultrasonic wave generator may produce a unique array of LIDAR signatures that can be detected and mapped, thereby potentially revealing any landmines.

The technology synergy approach exploits the unique strengths of the combined functionality of individual technologies and may present new and more informative types of data. By combining technologies, this approach may also help to mitigate or eliminate the deficiencies of individual technologies. Although conceptually promising, this approach may require a longer term investment.

SECTION 4

ENDNOTES

[1] David L. Hall and James Llinas, “An Introduction to Multisensor Data Fusion,” Proceedings of the IEEE, Volume 85, Number 1, January 1997, pg. 6.

[2] Ibid, pg. 8.

[3] Ibid, pg. 8.

[4] Ibid, pg. 14.

[5] Telephone interview with Moshe Kam, Data Fusion Laboratory, Drexel University, June 20, 1997. See also David L. Hall and James Llinas, “An Introduction to Multisensor Data Fusion,” Proceedings of the IEEE, Volume 85, Number 1, January 1997, pg. 16.

[6] Telephone interview with Tom Claytor, Non-Destructive Testing and Evaluation Team, Los Alamos National Laboratory, June 20, 1997.

SECTION 5

# FOLLOW-ON ASSESSMENT OF SELECTED SYSTEMS

## 5.1 INTRODUCTION.

In response to further DSWA guidance, seven of the 22 technologies/systems originally examined in the Task 1, Assessment #1 literature survey (and discussed in Section 3) were investigated in greater depth. This follow-up study, called Assessment 2, addressed:

- JAYCOR vehicle-mounted standoff landmine detection system (GPR)
- AlliedSignal minefield reconnaissance and detector (MIRADOR) system (GPR, IR)
- Army Research Laboratory boom-mounted, ultra-wideband radar system
- Time Domain System, Incorporated, ultra-wideband radar system
- SRI International aerial detection systems (SAR/GPR)
- Ongoing research efforts at the Canadian Defence Research Establishment Suffield
- Ongoing research efforts at the European Commission Joint Research Centre
- Per DSWA request, further analysis was also made of the developmental status and WAD-applicability of Lawrence Livermore National Laboratory's micropower impulse radar (MIR), of the U.S. Army's Airborne Standoff Minefield Detection System (ASTAMIDS), and of the U.S. Marine Corps' Coastal Battlefield Reconnaissance and Analysis (COBRA) system.

In addition, an analysis was made of the Proceedings of the National Societies of Electrical Engineers' 7-9 October 1996 Edinburgh Conference on the Detection of Abandoned Landmines for additional technologies of potential applicability to wide-area detection.

Original or current developers were contacted directly to ascertain the current status of their systems or technologies. To the extent it was (or could be made) available, information was sought on these systems' physical parameters, operational capabilities, developmental status and schedule, funding, and potential effectiveness. Assessments were made based upon the information provided. A standard against which effectiveness might be judged was specified by DSWA as an "80% or better probability of detecting an APL minefield (containing plastic and metal mines) in an open sandy terrain (or other well characterized terrains)." However, few of the developers could estimate the potential to achieve this standard due to the relative immaturity of their system or technology.

A synopsis of the findings for Assessment 2 is provided in Table 5-1. The column titled "Applicability to WAD" in Table 5-1 addresses the potential viability of a given system's technical approach for WAD applications and does not denote the developmental status of the system nor its functional capabilities.

Detailed system assessments, including points of contact, follow Table 5-1.

**Table 5-1. Synopsis of Assessment 2 findings.**

| SYSTEM | TECHNOLOGY | STATUS | APPLICABILITY TO WAD |
|---|---|---|---|
| JAYCOR Vehicle-mounted Standoff Landmine Detection System | GPR; quantum-well FLIR to be added | Baseline testing to begin 8/97, advanced technology demonstrations to begin 6/98 | Poor to Marginal - vehicle-mounted, designed for detecting ATL |
| AlliedSignal Minefield Reconnaissance and Detector System (MIRADOR) | GPR and EMI, with IR or visual camera | Work ceased March 1990, no further efforts planned at AlliedSignal; unit may be sent to Univ. of Missouri at Rolla | Poor to Marginal - vehicle-mounted; testing focussed on ATL detection |
| Army Research Laboratory Boom-mounted, Ultra-wideband Radar System | UWB GPR | Last tested at Aberdeen Proving Ground 10/96; currently addressing system improvements | Marginal to Good - must address limitations of single-technology approach and performance, translation to aerial platform |
| Time Domain Systems, Inc., Ultra-wideband Radar System | UWB GPR | Conceptual; no existing system; proof-of-principal testing performed | Marginal to Good - must address limitations of single-technology approach |
| SRI International Aerial Detection Systems | UWB SAR; addition of IR and hyperspectral under investigation | Three FOLPEN aerial detection systems operational, further tests pending; multi-sensor integration pending | Marginal to Good - must address limitations of single-technology approach |
| Canadian Defence Research Establishment Suffield Efforts | Hyperspectral imagery | Only preliminary testing to date of Compact Airborne Spectrographic Imager (CASI); improvements pending | Marginal to Good - limited by single-technology approach; cannot detect buried mines |
| European Commission Joint Research Centre Efforts | Unknown; possibly some airborne systems | Details unavailable; possible use of U.S. sensors by DG-VIII office | Further information necessary for assessment |
| Lawrence Livermore National Laboratory Micropower Impulse Radar (MIR) | UWB GPR | Tested in prototype look-down array, primarily for point-source detection | Poor - single technology, extremely short detection range; only applicable for point source detection |
| U.S. Army Airborne Standoff Minefield Detection System (ASTAMIDS) | IR (passive and passive/active, respectively) | Two systems (Raytheon and Northrop Grumman) tested in 1996 for SSO application, found inadequate; further system developments on-going, FY98 transition to EMD phase | Marginal to Good - limited by reliance on one waverange (IR); designed for ATL detection |
| U.S. Marine Corps Coastal Battlefield Reconnaissance and Analysis (COBRA) | Multispectral video imagery | Field tests in August 1997; system improvements with commercially available equipment on-going | Marginal to Good - may be effective for coast, but requires daylight and cannot detect buried mines; designed for ATL minefield detection |

## 5.2 JAYCOR VEHICLE-MOUNTED STANDOFF LANDMINE DETECTION SYSTEM.

JAYCOR has worked on three iterations of a ground-vehicle-mounted anti-tank landmine (ATL) detection system. The first effort, a 1.5 year undertaking, involved the construction and testing of a laboratory prototype on a golf cart platform. Following that, JAYCOR mounted a ground-penetrating radar system on a jeep platform. That one-year effort resulted in a prototype system that used a one-kW output, stepped continuous wave signal directed and received through three horn antennas to detect, locate, and identify targets. Using an automated data processor, ATL was distinguished from ground clutter by its resonance structure, the signature for which was stored in a proprietary database developed by Lockheed Martin Sanders. System resolution was set to 25 cm to limit the data load caused by smaller clutter. While this resolution is adequate for detecting ATL but not APL, JAYCOR developers indicated that APL detection may be a future design goal. They also indicated that the signatures for such APL as M-14s could be seen in their radar images, but currently were too small to distinguish clearly from ground clutter.

The Jeep-mounted system achieved a 3 m-wide swath with a stand-off range of 10 to 30 meters while the Jeep to which it was mounted moved at approximately 2.5 kph. No marking capability other than physical marking was included in the system design. Tests were made to detect ATL in sandy and moist adobe clay soil, buried flush to the surface and down to 8 inches deep. The system experienced some overheating problems, but is claimed to have achieved tested detection rates of approximately 75% with about one to two false alarms per 50 square meters. It was also claimed to be able to detect unburied mines up to 60 meters away. However, it was found that snow and excessively moist soil impede the detection of buried mines.

Work is proceeding on a prototype Humvee-mounted ATL detection system that includes the ground-penetrating radar as well as a quantum well FLIR, which would be used to confirm targets, potentially improving system performance. Upgrades will also be made in computer controls and data processing capabilities. The system's 3 dB detection beam is 60 degrees wide, but can be made wider, depending on the application. The design goal is a system that can detect ATL buried up to eight inches, within an eight meter swath and at a stand-off range of 60 meters, with an effectiveness of 80% to 90% and one false alarm per 50 square meters. The vehicle is allowed a maximum forward progression of 5 kph. The radar of this newest system weighs 100 lbs., the computer weighs 50 lbs., and the three antennas weigh 30 lbs. each. The system also requires a two kilowatt power source, for which a generator is hung off the back of the Humvee. This system is also to include GPS technology for marking detected landmines.
Researchers at TRW Space and Electronics Group in California addressed the detection using passive MMW sensors of MMW radiation (at 44Ghz) emitted from an environment containing metal landmines laid on the surface of, or buried in, dry sand. MMW radiation from soil, which has a high emissivity and low reflectivity, depends mostly on its temperature, while MMW radiation from metal, which has a high reflectivity and low emissivity, depends mostly on the presence of ambient radiation. TRW concludes from their research that, using passive MMW sensors under ideal laboratory conditions, metal can be detected when buried up to three inches in dry sand.[1]Field calibration tests of the Humvee-based system were held at Fort A.P. Hill in June 1997. JAYCOR engineers indicate it did not perform well during those tests due to local RF transmissions (i.e., from cell phones, pagers) interfering with sensor operation. However, the system, when operated after the tests in an "RF-quiet" area, performed very well, detecting the majority of randomly-placed plastic and metal APL buried up to 6 inches deep. JAYCOR indicates that system hardware currently operates as planned, but system software is not yet fully developed. Complete field tests of the Humvee-based system are planned for June 1998, possibly at Fort A.P. Hill.

The jeep-mounted system was developed at a cost of $1.8 million, while the Humvee-mounted system has a budget of $8 million, which is provided through the U.S. Army Night Vision and Electronics Sensors Directorate (CECOM/NVESD) at Fort Belvoir. Tom Broach is a point of contact at CECOM/NVESD.

System developers at JAYCOR indicate that there are potential prospects for an aerial platform-based system, but current efforts will focus on a ground vehicle-based system. An aerial system will require much faster data processors. JAYCOR personnel also stated that Lockheed Martin Sanders developers, who are developing the algorithms to integrate the GPR system with the FLIR, may be very interested in aerial applications.

**Assessment**: Though limited as a ground-based system for non-WAD applications, this system may satisfy ground-truthing/proofing requirement following WAD activities. The ability to detect and recognize all possible resonance signatures (including APL and ATL) for all environments may also need further development and testing. Given the methodical developmental approach taken by JAYCOR, particularly with the HUMVEE-based system, this project warrants monitoring and a reassessment of future developments for potential deployment on an aerial platform.

Point of Contact: Burt Davis, JAYCOR, Albuquerque, NM, (505) 344-7455

### 5.3 ALLIEDSIGNAL MINEFIELD RECONNAISSANCE AND DETECTOR (MIRADOR) SYSTEM.

MIRADOR, a commercially developed system that achieved the level of engineering prototype, has not been worked on at AlliedSignal/Kirtland Operations (formerly EG&G) since March of 1990, and no further efforts are planned there. The ground-mobile system, based on a golf-cart-sized platform, employed a pulsed ground-penetrating radar whose output was integrated in a data fusion processor with the output of a pulsed inductive metal detector (also called an electromagnetic induction (EMI) sensor). The radar had a pulse repetition frequency of 5 MHZ and a one nanosecond monocycle pulse, a dynamic range of 55 dB, an effective bandwidth of 0.6 - 9+ GHz, and tapered impedance transverse electromagnetic (TEM) mode horn antennas. The GPR operated in a bistatic mode (i.e., with separate transmitter and receiver). The EMI sensor operated at a 200 MHZ repetition rate. An optical (visual or IR) camera or videotape sensor was also employed, although its data was not integrated with the other outputs. The detector suite was approximately 3 feet by 4 feet by 5 feet in volume excluding the antennas, weighed about 500 lbs., and drew less than 2.5 kW.

A March 1990 Final Test Report by EG&G's Energy Measurement division indicates the system achieved a detection effectiveness of 95% for buried and surface-laid mines with an average false alarm rate of 2.4 per 1,000 square feet. However, these field tests were performed under highly controlled conditions and focussed on the detection of eight different anti-tank landmines. Testing was performed on only two common anti-personnel landmines (a six-inch standard mine and an M-16 mine), resulting in detection rates of 20-35% and 90-93%, respectively; these results were not included in the overall MIRADOR performance summary results. Moreover, test results indicated MIRADOR performed poorly in discriminating actual landmines from mine-like targets, such as a soda can.

MIRADOR is currently stored at Fort Leonard Wood, but might be transferred to the robotics program at the University of Missouri at Rolla (UMR), where additional work on the technology may be pursued. However, DOE will retain AlliedSignal/Kirtland Operations' original patent on MIRADOR.

Developers at AlliedSignal stated that MIRADOR's sensor technology approach was sound (saying the sensors were and still are adequate to the task), but that the data processors were old technology and inadequate to the data processing demands. They noted that UMR will likely replace and upgrade those processing capabilities with newer and faster technology.

The development of a second-generation system known as the Improved Ground Mobile Mine Detection Testbed (IGMMDT) was initiated at EG&G prior to AlliedSignal's split from the parent company. The original IGMMDT developers stayed with AlliedSignal following that split. However, EG&G retained and continued the development of the IGMMDT, which, according to Allied/Signal personnel, was to have been tested at Fort A.P. Hill, VA, in late 1995; these tests may still be pending. The system was to employ dual-band infrared detectors, ground-penetrating radar, a metal detector, and a visual waveband detector. As a ground-based system that was supposed to travel at 3-5 kph, it would still prove highly limited for the wide-area detection mission. The project's COTR at the Night Vision and Electronic Sensors Directorate, CECOM Fort Belvoir, was cited as Terry Lee Hanshaw. The EG&G contact was cited as Phil Johnson, who is based at Management Systems, Inc. in Albuquerque, NM.

**Assessment**: MIRADOR was described by AlliedSignal developers as an inactive project. Its original design as a ground-mobile detection system limits its potential for wide-area detection. It may have served to verify minefield boundaries discerned first with wide-area sensors. Prospects for future MIRADOR development are unclear. As IGMMDT is also a ground-based system, it faces similar limits to WAD application. Both MIRADOR and IGMMDT employ data fusion, and both would appear to require the characterization of all items sought (i.e., all different types of landmines) for automated recognition.

Point of Contact: Michael Johnson, Project Management, Engineering Services, AlliedSignal/Kirtland Operations, (505) 844-3754.

## 5.4 ARMY RESEARCH LABORATORY BOOM-MOUNTED, ULTRA-WIDEBAND RADAR SYSTEM.[2]

In 1994, the U.S. Army Research Laboratory (ARL), located in Adelphi, Maryland, started a 6.2-level, Army-funded program to develop an ultra wideband radar system for the detection and location of near-surface landmines. As a result of their efforts, they have developed an experimental system which can collect data on the ability of ultra-wideband (UWB) synthetic aperture radar (SAR) to detect and identify buried targets or targets concealed by foliage. The system is comprised of a one-GHz-bandwidth, low frequency, fully polarimetric UWB SAR mounted to a mobile, 150-foot boomlift platform. The UWB SAR system is also modular, allowing ready exchange of different test components. The testbed included transverse electromagnetic (TEM) horn antennas, Tektronix 8-bit analog-to-digital (A/D) converters, Mercury i860 processors, six magneto-optical data storage disks, timing and control assembly, Geotronix 4000 position location subsystem, and a Sparc 2E operator interface. System control was performed by software and programmable logic. The SAR's Power Spectra 2-MW peak impulse transmitters produce an impulse waveform with spectral response ranging from 50 MHZ to over 1 GHz. The 1 GHz bandwidth provides a 5-inch resolution in the range direction, while return processing yields 6-inch resolution in the cross-range direction. Pulses are transmitted sequentially to provide polarimetric data. The radar is operated at a pulse repetition frequency of 700 Hz.

ARL's boomlift traveled at about one kph during tests. ARL claims that this configuration allowed precisely controlled tests that reasonably well duplicate an aerial deployment and provide an adequate degree of freedom.  ARL also claims their UWB SAR system may be employed on helicopter platforms, thereby augmenting its wide-area capability.

Two foliage and ground penetrating radar experiments performed with this apparatus at the Aberdeen Proving Ground (APG), Maryland, and at the Yuma Proving Ground (YPG), Arizona, are discussed in a February 1997 report (upon which this assessment is based).  The APG environment supported foliage penetration tests, while YPG supported ground penetration tests.  Tests at APG involved scanning for vehicles and canonical targets in the clear as well as hidden by foliage, plus subsurface objects.  Images were generated from 7400 aperture positions over 740 m, yielding an image 230 m by 200 m.  Analysis of APG test data has resulted in data processing modifications that improve the system's radar signal-to-noise ratio.

Tests at the YPG Steel Crater test site focussed on the detection of a wide variety of subsurface targets buried in both a relatively homogenous soil layer and in naturally occurring clutter areas.  Soil characterization was performed to support the use of test data to verify electromagnetic models, which could then be used to predict radar performance in other soil conditions.  Tests showed that the Valmara 69 APL (plastic body, max dia = 130 mm, 3.3 kg, 205 mm high, non-explosive wt = 2.703 kg, mostly in metal, bounding fragmentation mine) could be detected.

Analyses using a method of moments model indicated that 4-inch APL were visible in the 400 MHZ to 1000 MHZ sub-band, while the metal, 14-inch diameter M20 mine was visible in the 300 MHZ to 500 MHZ sub-band.  This analysis was borne out by test findings, wherein the resonant frequencies of the different targets renders them more visible at different spectral frequencies.

The researchers conclude that low-frequency UWB SAR offers the potential to detect foliage-obstructed and subsurface targets.  They also state that their boom-mounted system is valuable in helping to determine the optimal frequency for detecting specific targets, and that it complements existing airborne low-frequency SAR systems by offering a highly controlled data collection tool with the same scanning depression angles.  They indicate that more work must be done to discriminate targets from clutter, thereby reducing the false alarm rate.

A TEM horn antenna has been incorporated into the system that extends the frequency coverage from 25 MHZ to 1 GHz, potentially improving the low-VHF return from man-made objects and reducing backscatter returns from clutter.  No test data are available yet on its performance.  In the future, a Litton Inertial Navigation System (INS) will be used with the Geotronics 4000 to provide a 50 Hz update rate for motion/positional data.  Also, commercially available analog-to-digital converters may be integrated into the system and evaluated.

**Assessment**:  Questions remain regarding problems posed by different types of soil, moisture content of soils, and electronic interference.  Additionally, target discrimination capabilities must be further developed to lower the false alarm rate and improve overall performance.  Further assessment must also be made of the system's potential for higher speed and less controlled applications, such as from a helicopter.  Moreover, the locational accuracy of the boom-mounted sensor system is uncertain, given its potential for swaying.

Point of Contact: Karl A. Kappra, U.S. Army Research Laboratory, Adelphi, MD, (301) 394-0848; e-mail: kkappra@arl.mil

## 5.5 TIME DOMAIN SYSTEMS, INC., ULTRA-WIDEBAND RADAR SYSTEM.

Time Domain Systems, Inc. (TDSI) works primarily on the development of covert communications technologies. They have developed highly undetectable (stealth) walkie-talkies for the U.S. Marine Corps and other parties. With this technology, they have produced what they claim is the first communications system whose broadcast range (tested to over 15 km, line-of-sight) exceeds its intercept range (less than 20 m). TDSI has applied the technology underlying their communications system to the development and construction of a breadboard-level radar system for detecting buried or hidden objects. Proof-of-concept tests demonstrated the ability to image a concrete sphere, as well as to detect the movement of an 8-inch-by-3-inch object behind the walls of a building at a range of 75 feet. TDSI developers indicate the test system included AC-powered transmitters that could fit into two medium-sized suitcases, and that the antennas were approximately 5 feet by 2 feet by 8 feet in size. The device operated in the UHF frequency band and was tested mostly in searching for foliage-hidden objects at a range of up to about 200 feet. TDSI indicates this range was limited by the relatively crude receiver used, and that performance and range could be significantly improved by using the much more capable processors now available. No TDSI radar system remains in existence, although it was indicated that another breadboard system could be constructed relatively quickly. With these R&D efforts, TDSI considers the feasibility of using their ultra-wideband technology for radar applications to be proven.

In TDSI's technical approach, the radar's return signal is compared to a Gaussian monocycle-based, time-gated, dithered (randomized) RF pulse output. The returned signal is picked up and compared using a correlating receiver (which serves as a matched filter), enabling the system to perform highly accurate ranging while achieving a processing gain of up to 50 dB. With an appropriately designed antenna array to achieve angular resolution, three-dimensional pictures can then be constructed from two-dimensional images. The system is operated at a very low electromagnetic frequency (in the RF range) to reduce absorption by the earth. TDSI developers also state that the system's base frequency of operation could be moved from 2 GHz to 4 GHz to improve object resolution or to 1 GHz to improve penetration, although that may take additional developmental effort. They also indicate that ultra-wideband transmissions do not interfere with military or commercial radars and radios.

TDSI developers state that the use of a coherent signal allows the return signal to be below the ambient noise level. Moreover, the technology's high bandwidth yields a greater range resolution and therefore greater potential image resolution of smaller objects. For example, TDSI claims resolution down to 13 mm ± 4.5 mm for the ideal communications scenario. While waveform distortion in GPR applications will result in somewhat diminished resolution, TDSI claims it can achieve a range resolution at least equal to, and likely better than, that of the best SAR technologies.

Signal attenuation by different media - for example, up to several dB per inch of soil - and by material boundaries imposes a minimum power requirement for GPR function. TDSI indicates they designed their system to have as high a pulse repetition frequency (PRF) as possible to keep the peak time domain power as low as possible. In addition, they state that by averaging the return of the very high PRF signals, their GPR system will have a much lower overall system power requirement because their coherent receiver adds the voltage, not the power, of the return signals. However, TDSI says that their coherent receiver technology allows them to build a system that uses one to two orders of magnitude lower power than other technical approaches. A TDSI developer indicated that a power source may be needed that supplies a 20 picosecond pulse of 2,000 volts at 50 ohms at a PRF of 20,000 times per second. It was noted that an adequately large and fast-pulsing power source may be available from a firm in St. Petersburg, Russia.

TDSI developers state that their technology has the capability to image objects buried up to one foot deep with a three inch resolution, although they do not specify a range at which this might be done. They suggested that would need to be determined experimentally. However, they pointed out that synthetic aperture radar systems require extensive data processing to compensate for the various angles and image overlaps before the "corrected" data can be used to construct an image. TDSI's ultra-wideband approach, however, involves using sparse array antennas for signal summing and angular resolution, wherein more antenna elements can achieve a better angular resolution. When combined with the greater range resolution available from their dithered pulse and high bandwidth approach, minimal pre-processing is needed prior to image processing, and higher accuracy images may be generated. This thereby lessens the computing and power requirement, time delays, and resultant system payload. However, TDSI's efforts to date have only focussed on medium (e.g., 200-foot) range experiments. They noted that aerial detection, while possible in principle, would require a very high data processing capability, the speed of which may limit the overall rate of object detection. It was postulated that a $10,000 to $20,000 Sun or Cray computer would probably need to be integrated into the system to handle those image processing requirements.

Because they consider themselves an "RF outfit," TDSI stated that all of the tomographic processing (the compilation of three-dimensional images from planar cross-sectional scans) and pattern recognition/correlation would be done outside of their company as they are too small and focussed an entity to handle such an effort. For their experiments with landmine detection, they hired the Jet Propulsion Laboratory (JPL) to process the large amounts of data generated by the radar system. JPL used their own tomographic software to produce the resultant radar images.

TDSI is also working on the development of an intrusive radar system that could scan the inside of a cruise missile. While TDSI's radar technology appears to resemble Lawrence Livermore National Laboratory's micropower impulse radar (MIR), TDSI developers state that MIR does not use a correlating receiver to compare return radar signals to those transmitted. They note that this is why the MIR range is only a few meters at best, while the TDSI radar has a significantly greater range. Moreover, TDSI developers stated that their technology was patented five years before MIR received its patent.

TDSI developers concluded that, while their radar technology might be among the best available for detecting all but the smallest landmines, it would require enough funding for them to forego some of their principal, communications-area development efforts and pursue the development of landmine detection technologies. With adequate support, they indicate a complete radar system could be built in one to two years. Such a system could also be developed by a TDSI licensee. However, it was noted that many of the components necessary for a radar system will likely be developed by TDSI over the next year as part of on-going communications technology R&D efforts.

**Assessment**: TDSI's technology is still evolving and would require the solution of many outstanding technical issues before a WAD capability could be achieved. However, given TDSI's on-going work, it merits monitoring the development of their technology and revisiting their status in one year's time. The future availability of new and more proven components may encourage other developers and licensees to pursue the development of a landmine detector, something TDSI does not appear inclined to do at this time.

Points of Contact: Alan Petroff and Paul Withington, Time Domain Systems, Inc., Huntsville, Alabama, (205) 922-0384

## 5.6 SRI INTERNATIONAL AERIAL DETECTION SYSTEMS.

SRI International has built ultra-wideband radar systems specifically for the wide-area detection of buried targets, unexploded ordnance, and landmines, and of foliage-obstructed targets. SRI's radar system uses ultra-wide bandwidths to form continuous, real-time scrolling images that are typically integrated with Global Positioning System information and then recorded onto optical disks. Their initiatives have focussed on a ground-based, trailer-mounted system that looks forward and down (30 degree from horizontal) with a range of about 100 feet; a down-looking, helicopter-borne system for vertical profiling; and sideband (±30° azimuthal beam), synthetic-aperture systems aboard fixed-wing platforms. The last of these comprise their foliage-penetration (or FOLPEN) systems, onto which SRI focusses most of its technical efforts relevant to wide-area landmine detection. The FOLPEN systems are capable of scanning a 2 km-wide swath at 220 kph, potentially offering the most rapid of wide-area detection approaches.

Three different FOLPEN radar systems have been mounted aboard separate fixed-wing aircraft. FOLPEN I is an operational, fixed-wing-borne SAR prototype first deployed in 1990 and upgraded in 1996. Originally fitted with HH dipole antennas, it now employs quad-ridged horns. The directly-sampled UWB SAR operates in the 100-600 MHZ range with a bandwidth of 500 MHZ, a pulse repetition frequency of 167 Hz, a peak voltage of 15 kV, and both VV and HH polarization. The system performs no real-time processing and stores its data on optical disc. It has a dual resolution of 1.0 m and 0.5 m and operates at altitudes of 1,000 to 5,000 feet. Motion compensation is performed using DGPS. SRI states that FOLPEN I is currently being upgraded for a response beyond 1 GHz for mine detection applications, with modifications for harmonic radar work also being drafted. SRI indicates the system will be available by mid-August of 1997.

FOLPEN II was built in 1991 and is still operational. Specifications include a 10 kV (peak) transmitter operating at a pulse repetition frequency of 200 Hz through a quad-ridged horn antenna. The UWB radar has a 200 MHZ bandwidth centered at 200, 300, 350, and 400 MHZ, with an additional 400 MHZ wide band from 200-600 MHZ. The system includes a coherent I/Q receiver with single (HH) polarization, DGPS for motion compensation, optical discs for continuous data storage, and limited real-time processing. (During real-time processing, it cannot provide motion compensation). SRI indicates FOLPEN II has a ground coverage rate of 150,000 $m^2$/second, operates from 1,000 to 10,000 feet in altitude, and provides real-time reduced-resolution SAR images. Resolution is stated as 1.0 m. FOLPEN II achieved ground penetration capabilities in 1992. The system, which is in storage pending transfer of its title from the government to SRI, has logged over 600 hours of flight time.

Built in 1993, FOLPEN III is similar to the FOLPEN II, but with the addition of a second polarization channel. SRI literature indicates the system can collect HH, VV, and VH data, and is capable of real-time, on-board processing as well as tape data storage. The system employs either dipole or horn antennas, depending on the portion of airframe used, and operates at 1,000 to 6,000 feet in altitude. Peak transmitter voltage is 30 kV, and range-cropping motion compensation is performed using GPS/INS. SRI claims FOLPEN III can provide full-resolution SAR images with multi-polarization, dual resolution (0.5 and 1.0 m), and automated target nomination at a coverage rate of 150,000 $m^2$/second. The system covers the 200-600 MHZ frequency range with 200 MHZ of bandwidth. This system was designed for applications in Central and South America and first flown in 1994. Stereo SAR imaging was incorporated in 1995. The system, which has logged 300-400 hours of flight time, is presently operational and awaits modifications for installation aboard a smaller aircraft - a Jetstream-31 - for a twelve-month operational deployment.

SRI's literature also indicates they undertook initiatives with van- and helicopter-based vertical profilers between 1990 and 1993 for tunnel, bunker, ordnance, and mine detection; a 250 lb., 550 W SAR designed for deployment aboard a UAV between 1994 and 1997; and unspecified, classified SAR imager programs.

Radar data was collected in June 1993 tests in the Yuma, Arizona desert that demonstrated the ability of the FOLPEN II system to detect M-20 metal ATL on the ground's surface as well as buried 1 cm to 12 cm deep. It was unable, however, to detect either buried or surface-laid M-80 plastic ATL and Valmara-69 APL. The plastic mine was difficult to discriminate from the surrounding soil due to their very similar dielectric constants. The smaller-sized Valmara-69 APL was difficult to detect due to its small radar cross-section, given the FOLPEN's resolution of only 1 m by 1 m.

In 1994, tests were performed at the Jefferson Proving Ground, Indiana, to evaluate the state of the art in unexploded ordnance detection and remediation technologies. SRI's van-mounted, ground-based system was evaluated in tests over a 40-acre landmine detection test site, of which the system only succeeded in searching 13 acres in a one-week period. Tests of the SRI aerial platform-based systems (the helicopter-based and FOLPEN II systems) were performed over a separate 80-acre detection test site, also at Jefferson Proving Ground. The tests found that the ground-based system performed relatively poorly, producing significant false declarations per ordnance item detected. The tests further found that the aerial platform-mounted systems could reliably detect almost none of the buried test landmines. It was noted that the wet, clay soil conditions at Jefferson Proving Ground, combined with standing water on the surface, limited the performance of the aerial platform-based systems.

SRI developers stated that the FOLPEN systems (of which the FOLPEN I was indicated as best for landmine detection) are now routinely capable of detecting landmines down to 0.5 meters deep in a desert environment (and as deep as 2 meters, maximum, for larger targets), while they can only penetrate a few centimeters down into wet clay. Additionally, standing water causes forward signal scatter (reflection), which greatly impedes detection. The FOLPEN GPR sensors, SRI claims, can detect 100% of metal ATL with a false alarm rate (FAR) of only 0.1; 100% of plastic ATL with a FAR of 1.0; sporadic detection of metal APL (no precise measure specified nor FAR indicated); and a "low percentage" of plastic APL. In the case of plastic APL, it was suggested that the ground might be soaked to improve the ratio of soil-to-plastic APL dielectric constants, thereby improving the contrast between them; this approach awaits future testing with their ground-based system. Overall, SRI developers indicate that the FOLPEN system can "readily achieve" an 80% detection rate in dry sand for all metal ATL and APL. Plastic ATL and plastic APL might be detectable with the incorporation of hyperspectral imagery and thermal FLIR.

SRI developers indicate that, while they are currently using a single sensor technology - GPR - they are also investigating the incorporation of hyperspectral imagery and thermal infrared sensors. Their approach would employ the synergistic fusion of all three technologies, with the potential to greatly enhance overall system performance. They stress that the single sensor approach will likely not provide the high probability of detection and low probability of false alarm necessary for humanitarian demining.

SRI plans to conduct additional tests of the ground-based and aerial FOLPEN systems. Their original proof-of-principle efforts were sponsored under DARPA's Steel Crater program, although currently refurbishments to FOLPEN I are self-funded. They have also done work, funded by the U.S. Army Corps of Engineers, in the area of unexploded ordnance detection. They are seeking funding of further proof-of-principle activities, particularly multi-sensor integration and data evaluation, to enhance the ability to differentiate between mine types.

**Assessment**: SRI initiatives are directly targeted at the wide-area detection of landmines and should be closely monitored. While the results of early tests at Jefferson Proving Ground were not promising, the evolution of SRI's technologies appears to be leading toward viable systems. SRI's current detection capability claims are significant relative to other developers, although SRI developers acknowledge the limitations of their systems for the stringent demands of demining. The results of upcoming tests should be assessed to determine their progress. Moreover, SRI's plans to integrate different sensors through data fusion may yield even better capabilities and may provide an empirical base for knowledge about multi-sensor aerial detection.

Point of Contact: Dr. Roger Vickers, SRI International, (415) 859-4422

## 5.7 ONGOING RESEARCH EFFORTS AT THE CANADIAN DEFENCE RESEARCH ESTABLISHMENT SUFFIELD.

Because of continuing Canadian involvement with UN peacekeeping and humanitarian missions, the Canadian Defence Research Establishment Suffield (DRES) is focussing some of its development efforts on dual-use technologies, i.e., those that could satisfy both military and humanitarian applications. In the area of landmine RDT&E, DRES concentrates on detection and on neutralization. Their early detection efforts addressed magnetometers, which detect ferrous metal, and pulsed electromagnetic induction (EMI), which detects all metallic objects. (DRES researchers note that EMI has no airborne role since its effectiveness diminishes as $1/r^6$). DRES started an improved landmine detection program (ILDP), which addresses the detection of low-metal mines from a ground-based vehicle. The improved landmine detection system (ILDS) they created employs FLIR, GPR, and EMI, which are integrated through data fusion. The system scans for potential "hits" on the different sensors, then evaluates the find with a towed thermal neutron activation (TNA) sensor. DRES' TNA sensor, somewhat heavier but faster than the version used in the U.S., measures about 2'x2'x2' and weighs about 550 lbs. (plus 100 lbs. of electronics). It requires from a few seconds to up to a couple of minutes to verify the presence of the quantities of nitrogen-based explosives found in mines. The system employs automatic target recognition (ATR), but also uses a "man-in-the-loop" for interpretation of the IR images.

DRES also assessed the usefulness of explosive vapor detectors, but found they could only determine the presence of explosives, not the precise location. They note that DARPA, however, is pursuing this approach.

In 1984, DRES began investigating the potential for airborne landmine detection with pilot studies that examined all of the major sensing technologies (radar, IR, UV, MMW, visible wavelength, acoustic, EMI, magnetometry, and others). UV sensors were discounted after analysis because much ground vegetation looks like mines in the UV spectrum. Visible light was not pursued at first, but was eventually included with the use of hyperspectral sensing (see below). Active IR was found to have some potential, although the technology is limited by speckle (the strong variation in reflectivity across an object's surface) and is strictly limited to searches for surface-laid mines. Attempts were made to employ monochromatic imagery to obtain mine profiles and ranges, where range information was used to delete speckle, but this, too, was only useful for surface-laid mines. Tests on active IR scanning were made from a tower and DRES never progressed with the technology beyond the experimental stage due to the high cost of developing an airborne system. Passive IR was also assessed, and development of an airborne passive scanner was also not pursued due to high cost. Passive IR is still being studied under the ground vehicle detection program.

Following their IR investigations, DRES purchased a commercially available airborne hyperspectral imaging system. This compact airborne spectrographic imager (CASI) was purchased from ITRES. Ltd, in Calgary Canada, for approximately $250,000 (U.S.). Its components include a control box and monitor similar in size to a home personal computer, and a sensor head that measures about 1'x1'x0.5'. CASI employs a programmable hyperspectral imager that functions in 288 bands, although the system developers indicate this capability will soon be expanded to 512 bands. The system functions down to about a 2.5 nanometer-wide band and up to a 545 spectral range that can be placed between 400 and 1000 nanometers. These spectral ranges are fully programmable while in-flight. CASI looks at the spectra reflected from a mine's surface, thereby requiring sunlight or other illumination. DRES and ITRES technologists incorporated the ability to compensate for environmental radiance. DRES found that camouflage may defeat visual perception, but coincidently happens to increase the signal in other spectral bands.

CASI is not currently designed for real-time applications. Since system testing began in 1989, data has been collected and stored aboard CASI for processing upon return to a home base. The system has had up to a 100% airborne detection rate for surface-laid surrogate mines, which were actually carpet squares with a spectral signature similar to mine paint 2500 $cm^2$ in area (similar in size to an ATL). It has detected real mines as small as 70 $cm^2$ from ground-based platforms. However, this detection requires an unimpeded line of sight to at least part of the mine. DRES technologists have stated that system resolution may be improved and smaller targets may be captured by scanning at select spectral bands or across the system's entire bandwidth, perhaps from a slow-moving helicopter.

CASI has been used to scan for, and can slightly detect, buried landmines, although tall foliage defeats the system. DRES estimates it has had perhaps a 60% buried mine detection rate by scanning for different surface properties. These properties include surface areas originally dug out for landmine emplacement that have since settled and in which water now pools; areas where the recently disturbed soil around new mine emplacements is differently colored (although this effect dissipates in about two days); spots of dying or stressed foliage indicating the top layer of sod was once peeled back for mine emplacement; the presence of explosive particulates trapped in foliage; and possibly areas in which vegetation growth has been enhanced by the availability of extra nitrogen from explosive materials. They also addressed detection of the long slit in the ground left when landmines are machine-emplaced.

DRES tested CASI for detecting buried landmines whose positions had been precisely mapped. One month's test data was collected for APL and ATL buried in areas of bare soil, short vegetation (grasses), and medium-length vegetation (including blueberry bushes). Their results indicated a detection rate in bare soil of 70% with a false alarm rate (FAR) of 0.52; 94% with a FAR of 0.17 in short vegetation; and 55% with a FAR of 0.34 in medium-length vegetation. DRES points out that these results were calculated by cross-referencing suspected detections with the plot of known mine locations, thus they are not representative of tests involving targets of unknown position. In these results, DRES also does not quantify the difference between APL and ATL detection rates, but notes that the former is less than the latter on average.

DRES has also studied the feasibility of using remote aerial radar that functions in the centimeter to tens-of-centimeters wavelengths. Both passive and active technologies were assessed. Passive MMW radar was also evaluated. This study was never advanced beyond the conceptual and bench-scale assessment level. DRES determined that the operational requirements of this type of system, such as a 50-foot maximum altitude and an extremely narrow beam width, were too constraining. No further work was pursued in this area.

Upcoming DRES work includes the development of real-time data processing on-board the aircraft, an active laser scanning system, and improvements to the scanning swath width and spectral range of the CASI. DRES has been pursuing additional hyperspectral capabilities to detect buried mines, with particular emphasis on the IR wavelengths. This would include extending into short-wave IR, which may better detect structures in the substrata, and into long-wave IR. DRES and ITRES are also investigating ways of increasing the system image capability to 1024 pixels. This may require the coregistering of 2 cameras, which will be assessed against employing a large single CCD; each approach presents its own technical difficulties. Additionally, thermal hyperspectral IR imaging using cooled sensors may be investigated, although this approach, DRES researchers have indicated, will require additional funding.

**Assessment:** DRES' technologies and approaches to wide-area detection are both similar to others' and unique. They appear to be taking a measured approach to landmine detection commensurate with available funding. This is represented by their assessment of all major sensor types prior to incorporating them into composite systems. Moreover, DRES has likely reduced their overall RDT&E costs by adapting commercially available systems.

DRES' test results do not appear to exceed others' accomplishments to date, and they have indicated that their tests are somewhat preliminary and do not necessarily provide conclusive performance data. Further, more rigorous evaluations will be necessary as their systems evolve and mature. They will also have to demonstrate the ability to detect and locate APL (as distinct from ATL) for the widest range of environmental and geographic conditions. In particular, their system's capability to work through atmospheric interference, penetrate foliage and greater depths of soil, and isolate mines from clutter must be improved and demonstrated.

DRES is directly addressing the need for wide-area landmine detection. Their efforts merit continued monitoring and possible engagement in joint developmental efforts.

Point of Contact: Dr. John McFee, Canadian Defence Research Establishment Suffield (DRES), (403) 544-4739

## 5.8 ONGOING RESEARCH EFFORTS AT THE EUROPEAN COMMISSION JOINT RESEARCH CENTRE.

The Joint Research Centre (JRC) coordinates the European Commission's (EC) RDT&E activities and analyses, most of which is contracted out. The JRC functions as technical consultants to the EC's financial managers and as technology evaluators. Because landmine clearance must precede a country's rebuilding, the EC has dedicated a portion of its humanitarian assistance program's infrastructure development funds to the development of landmine detection and clearance technologies.

Inquiry was made of the JRC's activities in technologies potentially applicable to wide area detection. A program sponsored by the EC's DG-VIII office in Belgium addresses finding the boundaries of mined and unmined areas, which would be verified with ground-based sensors and surveys. Details about the program were not readily available, but it appears the program concentrates on fusing existing sensors for detection. Marking may be accomplished by GPS or by using fixed (emplaced) markers and laser range finders. The system may also employ a low- and slow- flying aerial platform called Sky Van, which is manufactured by Shorts, a firm in Belfast, Northern Ireland. Several of the sensors employed may be of U.S. origin. Funding may already have been awarded to technical developers.

Most of the JRC's efforts focus on ground-based and hand-held landmine detection systems. A feasibility study of different detection technologies was performed by a JRC-sponsored consortium; the results of that study were expected to be made available to the EC by December 1997. As a follow-on effort, the JRC has invited developers to submit their proposals for developing, on a 50/50 cost-shared basis, technical elements (sensors, components, software, etc.) to be fitted into a composite mine detection system. The individual developers will be responsible for determining how their element(s) are to be integrated into the overall landmine detection system, although concerns about technology integration may be more fully addressed in a separate initiative in 1998. Government funding for this effort, known as the Espirit Program, is estimated at about $9 million, to be awarded to as many as several developers or as few as one, depending on the proposals submitted. Following an initial screening, awards will be decided in about September 1997 and made in 1998. The Espirit Program is to be run by the DG-III office in Belgium; the contact there is Mr. Patrick Van Hover.

The JRC has just recently finished constructing a mine field test range, allowing them to prove fusion algorithms and to control selected test variables. Feasibility tests of existing technologies and detectors, and tests to project potential data fusion requirements, will be conducted by the JRC at this test range. A contact regarding these tests and the tested technologies is Mr. Jeffrey Van Orden, who controls the feasibility contract and is based at the EC's offices in Belgium.

**Assessment**: EC initiatives focus mostly on ground-based detection systems, but on-going and planned investigations of aerial detection should be assessed. This survey could not obtain sufficient information to make an accurate assessment of those efforts. DSWA may wish to establish a liaison with the EC JRC through the appropriate U.S. government agency to allow closer interaction and information sharing with EC technologists.

Point of Contact: John Dean, 011-39-332-789-407

## 5.9 LAWRENCE LIVERMORE NATIONAL LABORATORY MICROPOWER IMPULSE RADAR.

Lawrence Livermore National Laboratory (LLNL) has put extensive effort into the development of its proprietary micropower impulse radar (MIR), a very-low-power, highly compact, high-resolution radar and imaging device. MIR was developed in 1993 as an evolution of government-sponsored work on radar combined with technology developed for LLNL's transient digitizer. Additional work to develop a man-portable landmine detector based on MIR was funded in early 1996 as an Advanced Technology RDT&E Program within DSWA's Verification Technology Programs (HQ DSWA/PMA).

For landmine detection, the MIR-based system currently employs an ultra-wide bandwidth of 1 GHz within a frequency range of 1-4 GHz, with a pulse repetition frequency (PRF) of about 2 MHZ and a scan rate of 40 Hz. Design goals include an expected frequency range of 3-10 GHz, a PRF of 7 KHz - 100 MHZ, and a scan rate of 40 Hz - 5 KHz. With a 100 picosecond rise time, the system might then be capable of yielding about a 2 cm range resolution in typical soils. MIR's microwave pulse is dithered, which ensures that no interference occurs between separate MIR units. LLNL has also developed data processing algorithms that generate 2-D and 3-D images from the radar's data, aiding in distinguishing buried objects.

Besides the above-described man-portable landmine detector, LLNL envisions deploying an array of MIR units in a look-ahead configuration for roads or look-down configuration for off-road (highly cluttered) areas, mounted to a remotely-controlled ground vehicle. In such conceptual approaches as a look-ahead system, the field of view, a shallow-depth plane of about 2-4 $m^2$, would be scanned so that a 2-D aperture is synthesized, and data transmitted back to a remote data-processing and control location. Similarly, in a look-down system, an array would be mounted on an extended boom mounted to the front of an advancing vehicle to detect ATL and APL. The array would be scanned to produce a synthesized 2-D aperture, and the forward motion would be integrated through processing to yield 3-D images.

In a look-down prototype system, a single MIR sensor was deployed in a look-down mode for data collection and feasibility studies. Three-dimensional data was collected through calibrated-step scanning along the horizontal plane using the single sensor. The radar stand-off height was varied from 3 cm to 30 cm. A 486-level PC, employing diffraction tomography methods, took under 10 seconds to reconstruct a 2-D image, and required information to be entered previously about the media (air and ground), scan timing, and scan geometry. The system was able to detect M-19 and VS-2.2 landmines buried up to 5 cm deep. However, while the MIR-based system detects buried objects, full 3-D imaging may be needed to discriminate between landmines and other objects. Outstanding issues the developers seek to address include clutter reduction, enhanced resolution and contrast, electromagnetic attenuation by different media, multiple scattering, shadowing, dispersion, real-time operation, and full 3-D imaging speed.

Earlier LLNL work with a high-power radar-based landmine detector aids in current MIR development efforts. That previous system, whose power exceeds MIR’s by several orders of magnitude, had a stand-off range of only about 9 meters. Current developmental efforts using MIR have focussed on a design range of only 0.5 meters (in look-down mode) to 3.0 meters (in look-ahead mode). The basic performance criteria LLNL selected is the detection of an M14 APL buried up to 7.5 cm deep in a variety of soils. LLNL indicates it has been able to render 3-D images of known plastic and metallic landmine mock-ups buried in 5-10 cm of moist soil and in up to 30 cm or more of dry soil. LLNL efforts indicate that, while 2-D imaging may be used to detect a specific buried object, 3-D imaging may be necessary to distinguish it from other buried objects. However, the scan-geometry (MIR signature) of each object sought must first be entered into the MIR computer for comparison and identification purposes.

While currently still in the developmental stage for APL detection, the underlying technology of MIR has been functionally applied to or commercialized for detectors that find reinforcing steel bars in concrete; fluid level sensors; and motion detectors in alarm systems. As noted, however, evaluations of MIR potential as a landmine detector, begun within the past two years, have focussed on MIR as a point source detector and imager, not as a wide-area detection system.

**Assessment**: This application is anticipated to be very inexpensive. However, it does not currently offer an adequate degree of stand-off detection capability. The greatest stand-off range it has been tested at is 3 meters (although one recent report indicates a range in air of 10 meters), whereas aerial or other wide-area detection platforms will require much greater range capabilities. Moreover, while this application may provide detection and imaging capabilities in the near-term for point-source detection of known landmines, extensive efforts may be necessary to characterize the various targets sought (i.e., buried and surface landmines) required by the associated data processing computer.

Point of Contact: Captain Phil Hezeltine, DSWA Field Command, (505) 853-0650

## 5.10 U.S. ARMY AIRBORNE STANDOFF MINEFIELD DETECTION SYSTEM (ASTAMIDS).

The U.S. Army's Project Manager for Mines, Countermine, and Demolitions, Picatinny Arsenal, NJ, through the Countermine Division at Fort Belvoir, VA, is developing an Army tactical countermine system designed to support offensive military operations. This airborne standoff minefield detection system (ASTAMIDS) is being developed as a mission payload to detect minefields from a UAV platform. It is intended to enable the military commander to choose avenues of approach based on the locations of known mined areas.

The Joint Countermine Advanced Concept Technology Demonstration (JCM ACTD) program, involving efforts by the U.S. Navy, the U.S. Marine Corps, and the U.S. Army, also incorporates ASTAMIDS. As a joint-service program, JCM ACTD is tasked with ensuring the connectivity and integration of systems demonstration, balancing workloads, and avoiding duplication.

The combat developer for ASTAMIDS, the U.S. Army Engineer School, has specified system performance goals that include: locating mines/minefields to within 150 meters; a probability of detection of 80% for buried patterned mines, 90% for surface patterned mines, 80% for unpatterned scatterable mines, and 70% for buried nuisance mines on an unpaved road; and a false alarm rate of less than 0.5 per square kilometer with a single pass and 0.1 per square kilometer with "confirm" passes. The system must detect and identify mines day and night, in limited visibility conditions, and transmit near-real-time detection data to a ground control station. It must also meet the size, power, and weight constraints of the unmanned aerial vehicle (UAV) on which it is deployed, and data must be compressed and digitally transmitted for processing at a ground station. These physical constraints could be relaxed somewhat for humanitarian demining applications, however, if a larger aerial platform such as a helicopter were used, and data processing might be performed in real-time on-board.

In addition, ASTAMIDS is not required to function in heavily vegetated areas. While there is not a military countermine requirement for this, the Project Manager recognizes that this may be a limitation of the system in a humanitarian demining application.

The Army has determined that a 25 mm sensor resolution is necessary to see the smallest ATL, which are approximately 100 mm in diameter. They also determined that computer-aided target recognition is necessary, given the high data acquisition rates and potential ground clutter.

ASTAMIDS employs a minefield detection algorithm and processor, or MIDAP. The MIDAP includes a high speed parallel array processor that applies a minefield detection algorithm to sensor imagery. After enhancing individual pixel data prior to imagery processing, the algorithm seeks out clusters of anomalies in the imagery to discern potential minefields. Mine-like targets are first assessed for their size and shape, then clusters are examined for patterns resembling buried, surface, or scattered minefields. Minefield boundaries can be best determined through multiple aerial sensor passes. On-board GPS is used for electronic locational marking.[3]

ASTAMIDS is currently in the program definition and risk reduction (PDRR) phase of the materiel acquisition cycle. Two ASTAMID systems are under development by two separate contractors: Northrop-Grumman employs a passive IR sensor to detect thermal signatures, while the Raytheon Company uses a combination of passive and active (laser-based) near-IR sensors.

The Northrop Grumman PDRR ASTAMIDS passive IR sensor operates in the 7.7 - 10.5 micron range with a sensitivity of 0.045$^{\circ}$K. It has a 80 microradian resolution, scanning 1 inch (in the fore-aft direction) at 1,000 feet altitude with a 215-foot swath. The sensor has a 4.96-inch aperture contained within a 7.25-inch diameter, 3-axis stabilized gimbal assembly. The system has an eight-to-one bandwidth compression. The overall package is expected to weigh about 100-110 pounds and draw 1,000 W average and 1,500 W peak power. The processor includes 16 Mercury Quad i860 modules operating at 40 MHZ; a 160 MB/second raceway interconnect bus; and 256 MB RAM. Data throughput is 5 GFLOPS, which equates to 12 million pixels/second. The system has a 6U VME form factor.

Deployed aboard a UAV, the Northrop Grumman ASTAMIDS requires direct (line-of-sight) optical access; it is impeded by trees, dense ground foliage, and adverse weather.

The Raytheon PDRR ASTAMIDS passive IR operates in the 7.9 - 10.3 micron range. It operates with 480 x 6 time delay integration (TDI), a mercury-cadmium-tellurium (HgCdTe) detector, and a 278 microradian resolution providing a scan of 1 inch at 300 feet altitude and up to a speed of 90 knots. The active IR sensor operates at 0.81 microns in two channels - reflectance and polarization. Its resolution is also one inch at 300 feet. The overall system scans a field of view of 3.8$^{\circ}$ x 40$^{\circ}$, yielding a swath width of 215 feet, and has a sensitivity of 0.05$^{\circ}$K. The system has a 3-inch aperture packaged in a 13.9-inch diameter assembly with yaw axis gimbal stabilization and pitch-and-roll scan mirror stabilization. Overall projected weight is 100-110 pounds and power consumption is projected at 1,000 W average, 1,500 W peak. The Raytheon system employs a distributed array processor (DAP) Gamma 4000 SIMD parallel processor, which operates at 40 MHZ. Its 4096 processors are each connected to their nearest neighbor. System throughput is 4 GFLOPS, equating to 10 million pixels per second. The system has a 252 MB RAM memory and a 6U VME form factor.

The Army has worked to reconfigure ASTAMIDS for use in support of the Army Forces in Bosnia. This Stability and Sustainment Operation (SSO) application is similar to most humanitarian demining applications and would allow ASTAMIDS more latitude in size, weight, and power constraints if it was carried aboard a larger aerial platform. Moreover, because demining typically is done in a non-hostile environment, more time can be taken in locating minefields or mines, operators can wait for favorable flight and detection conditions, and data processing need not be done in real time. However, demining requires much higher detection rates, locational accuracy in areas used by civilian populations must be much better than the 150 meters specified in the ORD, and the system must be able to identify both mined and cleared areas.

To prepare for the Bosnia support mission, the Army mounted each of the ASTAMIDS prototypes aboard a Blackhawk helicopter and subjected them to testing at Aberdeen Proving Ground in 1996. It was confirmed in those tests that the resolution of neither ASTAMIDS at the time was fine enough to detect APL. Moreover, the systems had limited automated target recognition (ATR) capability at this stage of their development. The systems' performance in these preliminary tests was judged inadequate to merit their deployment to Bosnia at the time of the test. The assessment did yield useful data that supported engineering changes in the systems. Moreover, the Army indicates that subsequent post-processing of stored data by Northrop Grumman shows the results may be more promising than first indicated. As a result, the Army may still decide to field the system to Bosnia following additional testing and if funding is available. The Army will also compare the effectiveness of man-in-the-loop target recognition against automated target recognition for potential use in a deployed system.

As of mid-June 1997, comparative tests of the two systems, under the PDRR schedule, are being performed at Fort Huachuca, Arizona, to form the basis for transition into the engineering and manufacturing development (EMD) phase in FY98. (NOTE: In August 1997, as this report was in final draft, an ASTAMIDS was sent to Bosnia for testing.)

Today, ASTAMIDS is closer to production than any other standoff minefield detection system. Though the system is designed for a military countermine role, it may have some applicability in humanitarian demining missions. A system capable of supporting regional minefield surveys could be achievable within the next five years. However, ASTAMIDS sensor costs are expected to be high, and skilled technicians will be needed to maintain the system. These factors may limit which countries or organizations can afford purchasing the system for demining applications; it may be necessary for a third party to purchase the system and lease out its services.

**Assessment:** The Project Manager has indicated ASTAMIDS' algorithm and hardware, which address a countermine mission, can be reconfigured as necessary to suit humanitarian demining missions. However, the system must be tested extensively to determine whether it is ultimately capable of achieving the more difficult requirements of accurately detecting APL. For example, current requirements for 150 meters' accuracy may not be adequate for humanitarian needs. Moreover, the system is not required to function in heavily vegetated areas, although system developers indicate ASTAMIDS can function in moderate grasses and vegetation. Finally, the projected cost for an ASTAMIDS may greatly exceed what those countries that most need it can afford. If ASTAMIDS can be adopted and proven for demining applications, the notion of third-party ownership and leasing may merit further consideration.

The Project Manager has undertaken to investigate ASTAMIDS' application to SSO situations; further monitoring of their tests and developments are merited to gauge their progress.

Point of Contact: Larry Nee, Chief, Countermine Division, Project Manager for Mines, Countermine, and Demolitions, Fort Belvoir, VA, (703) 704-1970

## 5.11 U.S. MARINE CORPS COASTAL BATTLEFIELD RECONNAISSANCE AND ANALYSIS (COBRA).

In a system development effort technologically related to ASTAMIDS, the U.S. Marine Corps (USMC) has performed an advanced-concept feasibility demonstration of image-based multispectral mine and minefield detection using intensified multispectral video sensors. While the Army countermine effort focuses on the land mass, the Marine Corps must conduct countermine operations during amphibious operations. This involves detection both on land and in the region below the high water mark. Their system, developed for remote reconnaissance of beaches prior to amphibious landings, is called the Coastal Battlefield Reconnaissance and Analysis (COBRA) system. Designed for deployment aboard the USMC's Pioneer UAV and equipped with a video downlink for remote control and potential data download, COBRA is intended for detecting minefields and landing barriers in such terrain as shallow water (up to 2-3 meters of relatively clear water, according to COBRA developers), beach, grass, a variety of vegetation, sand, and dirt. The system employs two Xybion IMC 201 multispectral video cameras with lenses and filter wheels that allow data collection in six spectral bands; each filter wheel rotates such that a different one of its six filters (with wavelengths ranging from 400 to 900 nanometers) is placed in the imaging plane every 1/30th of a second, corresponding to the camera's frame rate. The two down-looking cameras are aligned to cover a double swath width with adjacent field-of-view overlap. This passive subsystem produces standard RS-170 video output that is fed to a Hi-8 mm, triple-deck video recorder, while a forward-looking surveillance video is downlinked to a ground station for real-time control of the UAV.[4]

COBRA-recorded imagery is subjected to post-processing at a ground subsystem. The data is processed with a fully adaptive Constant False Alarm Rate (CFAR) algorithm and with patterned and scatterable minefield detection algorithms to provide minefield location and automatic minefield detection. An auto-registration algorithm first compensates for the alternating filters and platform movement through coarse translation estimation, warping, and image resampling. The resulting six-dimensional image is then analyzed to detect individual mines, wherein any mine-sized (local) spectral anomaly is labeled a mine. Minefield detection is then performed over a “minefield decision region” (i.e., within a one-second DGPS sampling window) by aggregating the individual mine detection results. Mapping is performed using GPS time updates taken during the surveying.[5]

In the fall of 1996, the COBRA/Pioneer system was tested at Camp Lejeune over the different environments for which it was designed. The system detected all surface-emplaced, ATL-based minefields over which it was flown. The system performed best in beach and intercoastal regions, with slightly higher probabilities of false alarm in grassy areas. Planned system improvements include the use of tunable multispectral sensors, enhanced ATR image processing, and advanced illumination using intensifiers, as well as potential multisensor applications.[6]

**Assessment:** COBRA is designed for minefield pattern recognition to meet its countermine mission requirements, as opposed to the detection of individual or buried mines, which are more likely in humanitarian demining situations. Moreover, many environments may prove more difficult for a demining system to function within than the COBRA’s intended field of operation - the littoral zone - due to potentially greater amounts and more diverse types of clutter and obscurants. Overall, though, this system may offer a potential approach for one aspect of APL detection in a specific environment. The monitoring of further COBRA development efforts is recommended.

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## 5.12 PROCEEDINGS OF THE EUREL INTERNATIONAL CONFERENCE ON THE DETECTION OF ABANDONED LAND MINES, 7-9 OCTOBER 1996.

Per DSWA tasking, a review was made of the Proceedings of the 7-9 October 1996 EUREL International Conference entitled “The Detection of Abandoned Land Mines: A Humanitarian Imperative Seeking A Technical Solution” to identify and analyze any technologies besides those identified in the initial study that might have applicability to wide-area detection. Of the numerous papers in the proceedings, only two addressed technologies or systems that might be applied to the WAD mission (one of which is DRES’ improved landmine detection system, described above), while another addresses a ground-based system whose research approach might prove helpful to the development of WAD devices. The systems and technologies presented in these three papers are examined below, including a discussion of apparent strengths and limitations and an overall assessment for each system.

5.12.1 "Optronic Line Scanning Remote Sensing for Initial Detection of Land Mines," by Mr. C. H. Hamon of Sagem S.A. in France.

According to the authors, optronic sensing involves the composition of an image from highly focussed line scans taken of an area from a stationary or moving platform. This technology purportedly avoids the excess data capture and processing requirements inherent in broadly focussed sensing techniques, where different area coordinates under investigation are either scanned several times or appear within a given field of view for long periods. This overlap is avoided in composing an image from line scans of a set area. The paper's authors propose creating optronic images using visual waveband devices (e.g., television, panoramic sensors, and linear cameras) and IR waveband sensors (e.g., forward-looking infrared, infrared search and track, and infrared line scanners). These sensors might complement other types of sensors, such as GPR or EMI, through data fusion.

Two optronic systems have been tested by the French Army on UAV platforms. Both systems employed sensors operating in the visible waveband and in the 8-12 micron IR waveband. The authors describe the results as promising and recommend optimizing the sensor design and software algorithms to improve the system.

Strengths: This type of system reduces the data processing load by avoiding the data input redundancy inherent in broad area scanners. This improves the overall gain for a given bandwidth and reduces storage requirements. This in turn, according to the author, improves data processing, data fusion, and georeferencing capabilities. Such an improvement may be necessary to scan and interpret the data associated with entire suspected minefields. In addition, the equipment associated with this technique is cited as relatively simple and easily ruggedized. It is also cited as being capable of scanning a wide lateral field (up to 180$^{o}$, with a swath equal to 3.4 times the height of the sensor above the ground) and adaptable to many speeds; this system type has been mounted on supersonic aircraft. Moreover, the authors state that Sagem heliborne line scanning systems already perform visual-spectrum mine detection.

Limitations: This approach can be restricted by environmental factors, such as dense vegetation, snow, surface water, fog, icing, or rain. Moreover, the technologies cited - visible spectrum and IR waveband sensors - do not address buried mines.

**Assessment**: While the sensors proposed do not detect buried mines, this approach may reduce the data collection and processing requirements of a full suite of integrated, surface-scanning and buried-object-imaging sensors. Another approach might be to employ line scanning with GPR or other technologies, thereby reducing the data processing load; however, the viability of this approach is unknown. Overall, additional consideration of optronic line scanning technology may be warranted.

5.12.2 "The Detection of Mines Using RF Millimetric Radiometry," by R. Frost, R. Appleby, S. Price, F. Nivelle, M. Allen, and G.D.H. Hawkins of TME Ltd. - UK, DRA - UK, and TME SA - France.

According to the authors, radiometry functioning in the 94 GHz and 104 GHz wave range can detect an object's emitted radiation (a function of its emissivity and its absolute temperature) and reflected radiation (due to the reflection of atmospheric millimeter and microwave radiation and to temperature differences between the object and its surrounding terrain). The authors describe mine detection tests performed on two devices, one known as the MITRE imaging radiometer developed by TME Ltd., and another, experimental unit called the MELCHIOR radiometer developed by TME SA. Both perform radiometric imaging under clear and inclement weather conditions of surface-laid landmines and those buried up to 5cm. The authors indicate that these radiometers can function at great stand-off ranges, and note that the MITRE imaging radiometer can be focused from 7m to infinity. The MELCHIOR radiometer is cited as having a thermal sensitivity of 0.5 $^{o}$K, which, if done at the appropriate time of day, should be adequate for distinguishing buried objects from their surroundings.

Radiometric imagers require a certain residence time to develop images. A 32x32 pixel image is cited as requiring one second at 0.28 $^{o}$K temperature sensitivity, while a more typical 256x256 pixel image with a temperature sensitivity of 0.4 $^{o}$K image would require 32 seconds.

The authors tested the effectiveness of the radiometers at various ranges. Photographs in their report appear to show that emplaced landmines are readily distinguishable, even if surface-emplaced in such conditions as rough grass, on a shale road at a range of 70m, and in wet weather.

Further tests are indicated as being planned for the MELCHIOR at close (about 2m), mid- (5-50m), and long (over 200m) ranges. IR sensors are also being added for comparison purposes and potential data fusion.

Strengths: Radiometery may provide a good complementary capability to other technologies. It appears to overcome problems inherent in IR and GPR systems.

Limitations: The time required to image even small areas may prove to be excessive for wide area detection. Also, it is unclear how this technology would function in a cluttered environment or where landmines are buried greater than the tested 5 cm. The MELCHIOR device is cited as weighing 60 kg, which may affect certain aerial platforms.

**Assessment**: This technology may warrant further investigation as a potential complement, through data fusion, to other technologies currently under investigation or in use. Due to the limited rate at which it can image an area, it may serve best in confirming the potential “finds” of other sensors.

5.12.3 “Airborne Multisensor System for the Autonomous Detection of Landmines,” by Klaus Scheerer, Bodenseewerk Geratetechnik GmbH, Germany.

The author describes the conceptual design of a multisensor system employing two high resolution IR sensors functioning in the 3-5 micron and 8-12 micron ranges; a Sony RGB video camera operating in the visible through near-infrared range in coordination with a near-IR laser illuminator; and a 10 GHz pulse-doppler radar with doppler beam sharpening. The proposed system would include on-board real-time image processing capabilities and be designed to operate autonomously aboard an unmanned aerial vehicle (UAV) with a data relay to a ground station. The system configuration was derived from data resulting from aerial tests performed between 1993 and 1996 of several electro-optical, millimeter wave, and state-of-the-art radar sensors. Deployment of the proposed multi-sensor system aboard a manned aerial vehicle is also discussed. An experimental system is planned for completion by 1999.

The described conceptual system design would be deployed in a 0.4 m diameter cylinder. The electro-optical sensors, which are to have identical fields of view, would use linear detection arrays synchronized to each other and the laser with a common polygon scanner with roll compensation. They would have a resolution of less than 0.5 mrad with a total field of view of ±26.5 degrees by 19 degrees. The radar system is to employ patch antennas integrated into the cylinder shell; down-range resolution is to be achieved by using a high bandwidth, while cross-range resolution is to be achieved using synthetic aperture processing. The radar and electro-optical fields of view are designed to coincide. Marking of detected mines will be accomplished in geodetic coordinates using inertial navigation sensors updated by GPS and image-aided navigation. Data is to be transmitted back to a ground station either directly or, where lines of site are obstructed, via a balloon-borne relay station.

After on-board data processing has been performed by a massively parallel computer, the resultant image is interpreted by a knowledge-based identification and classification system to determine the presence of a landmine.

Strengths: This appears to be a measured and well-structured approach to system design, including the independent testing of different sensor types from an aerial platform. The resultant conceptual design must be tested to determine the potential effectiveness of the data fusion strategy. The effectiveness of the particular combination of sensors chosen must be proven, but the individual sensors each brings their own strengths as well as limitations.

Limitations: The developers do not mention whether a variety of data fusion strategies will be tested. Also, the system has only three types of sensors, while other technologies might prove equally useful. The ability to coordinate the data of all four sensors must be demonstrated. The performance of all data processing on-board the system adds weight, power demands, and complexity to the system, particularly when the raw data could be transmitted to a ground station that does suffer from those constraints. A continuous transmission of imagery coordinates would ensure accurate marking of all suspect phenomena. Finally, the accurate automated interpretation of imagery may require the development of a data base that accommodates all possible landmines.

**Assessment**: This effort merits further monitoring to learn the results of planned testing, and to see what modifications are made as a result of those tests.

5.12.4 "The Improved Landmine Detection System," by B.M. Cain and T.V. Meidinger, Computing Devices Canada, Defence Research Establishment Suffield, Canada.

This paper discusses the Improved Landmine Detection System (ILDS) developed by the Defence Research Establishment Suffield (DRES) to detect metal and low-metal anti-tank landmines buried in roads. The ILDS, described in detail earlier in this report section, is a ground-mobile system that includes a teleoperated Remote Detection Vehicle (RDV) platform and a Command Vehicle (CV). The RDV carries all sensors, a navigation and marking system, and teleoperation equipment, while the CV follows about 500m behind the RDV carrying the control stations, including monitors and controls for the detectors and for RDV teleoperation. The authors state that the system, which was designed to detect anti-tank landmines (ATL), can detect anti-personnel landmines at a somewhat diminished performance level.

The authors indicate that technologies previously deemed unsuitable for military countermine operations may be used on the ILDS for humanitarian demining due to the different mission profile. They cite sensors, for example, whose low speed of operation render them unsuitable for countermine but may actually prove beneficial to slower demining activities as well as for data fusion requirements. This approach, they claim, enables them to more rapidly apply and test new possible solutions for demining using currently available technologies. The ILDS provides the platform for testing and quantifying system capabilities and limitations.

The ILDS is designed to operate in either a scanning or confirmation mode. The system moves forward at a constant speed when scanning, while operators interpret data streams for potential targets. If a potential target (i.e., a buried landmine) is identified, the system is stopped and applied in a confirmatory mode. A confirmation detector is then placed over the suspect spot and the detection process is performed. Physical markers are applied when the presence of a target is confirmed.

The ILDS employs three sensors for mobile scanning operations and one for stationary confirmation. The sensors were selected, based on DRES ordnance and landmine detection studies. Multiple sensors and data fusion are intended to improve overall probability of detection, overcome weaknesses in individual sensors, and reduce false alarm rates. The scanning sensors include a commercially available passive infrared (IR) camera, to detect the bulk thermal effect caused by a buried landmine and the surface thermal effect caused by surrounding perturbed soil; a minimum metal detector (MMD), which employs electromagnetic induction; and a ground penetrating radar, which employs a fixed antenna array mounted behind the MMD and provides coverage of a 3m swath. A thermal neutron activation (TNA) detector, which detects nitrogen content in soil, is employed as the stationary, point-source confirmation sensor.

High levels of nitrogen are often associated with the presence of explosives. The TNA sensor requires several seconds of residence at any given point to take a reading. Data fusion is performed on the outputs of the scanning sensors. A marking system physically indicates the location of a detected landmine. The entire system is mounted on a high-mobility, multi-wheeled remote detection vehicle.

Strengths: By addressing a limited scope of the landmine detection problem, DRES may have made feasible the use of otherwise unconsidered technologies, potentially yielding at least a partial landmine detection solution more rapidly. This approach also uses available technologies, reducing the time required to determine each sensor's capabilities and limitations. The ILDS could potentially serve to perform the ground-based verification necessary after any aerial detection operations and before neutralization activities are performed.

Limitations: This technology is not actually capable of wide-area detection. It is ground-based and is only designed to work on roads. Its sensors are limited in scope and may require further analysis of their ability to operate in a variety of terrains and environmental conditions. The use of TNA poses radiation and material handling/security concerns and requires a residence period that could greatly slow the rate of detection and confirmation. Moreover, the system, as designed, requires the use of well-trained operators to determine the presence of landmines. Finally, the system is currently only designed to detect ATL, while the larger problem to be addressed is the detection of APL.

**Assessment**: This system is basically unsuited for the wide-area APL detection mission. However, the technology selection and integration approach employed may be worth further consideration by other system developers.

SECTION 5

ENDNOTES

[1] "Sensor Technologies for the detection of antipersonnel mines; a survey of current research and system developments," European Union, taken from internet site, http:// diwww.epfl.ch/ w3lami/ detec/ artismcr96.html, 1996; Detection Technologies for Mines and Minelike Targets, SPIE conference proceedings, Orlando, Florida, April 1995.

[2] Report description and findings based upon a February 1997 paper, "Ultra-Wideband Foliage and Ground-Penetrating Radar Experiments," by Karl A. Kappra, Francis Le, Lam Nguyen, Tuan Ton, and Matthew Bennett, U.S. Army Research Laboratory, Adelphi, MD.

[3] Nee, Lawrence J., "Application of Sensor Systems to Mine Survey," Proceedings of the International Conference on Mine Clearance Technology, Agenda Item 5 (b), Technology for Mine Clearance Operations, published 11 June 1996.

[4] N.H. Witherspoon, J.H. Holloway, Jr., and M.A. Sartor, "The Evolution of Multispectral Mine Detection - The Beginnings of a Solution," presented at the Third International Airborne Remote Sensing Conference and Exhibition, 7-10 July 1997, Copenhagen, Denmark.

[5] Ibid.

[6] Ibid.

# SECTION 6

# FOLLOW-ON ASSESSMENT OF OTHER DISCIPLINES

## 6.1 INTRODUCTION.

Important advances in technology and systems development often result from technology transfer between fields. Unfortunately, the refined focus of many technologists can limit their perspective on potential applications of their technology to their specific mission. This can result in new technology development programs undertaken to meet a certain need when a full or partial solution may already exist in other disciplines. To complement the review of existing landmine detection-specific technologies, and given the complexity of the wide-area APL detection problem and the diversity of potential solutions, the DSWA sponsor also directed that a follow-on assessment, called Assessment 3, be made to identify potentially promising technologies within ten technical disciplines not immediately associated with APL detection.

The disciplines chosen for this assessment included:

- geology (including soil science and seismology)
- remote sensing
- archeology/paleontology
- medicine
- astrophysics
- drug sensors
- explosive sensors
- non-destructive evaluation
- civil engineering
- cameras (including scanners, imagery equipment, and photogrammetry).

These fields were selected based on their generally recognized use of technologies that scan, "look inside," and assess the contents or subsurface of otherwise closed systems. No importance should be construed from their order of presentation here.

Technologies unique to each field were sought. Some disciplines overlap to varying degrees, however, with respect to the technologies they employ. This resulted in a recurrence of certain technologies or technical themes. These observations are discussed in the findings below.

## 6.2 ASSESSMENT METHODOLOGY.

This effort focussed on identifying or eliciting notional applications of the different disciplines' technologies to the APL WAD task, as proffered by the technologists themselves. For each of the disciplines, major industrial, professional, academic, and governmental organizations involved in the development of technologies in their respective fields were contacted. Specialists were sought with the greatest familiarity with their discipline's technologies and their potential application. These specialists were informed of the general wide-area landmine detection task and questioned as to the potential applicability of their technologies. Because this investigation often involved technologists who are not familiar with APL detection, a generic characterization of an anti-personnel landmine was postulated, against which the use of new technological detection methodologies could be hypothesized. In the interest of promoting discussion about solutions that might achieve different thresholds of performance, information about both APL and ATL was provided. Specifically, technologists were informed that a landmine can be described by its physical attributes and its affect on, or differences from, surrounding terrain; nominal characteristics are:

1. Size - APL range in width from about 6 to 15 cm. ATL can range in width from about 10 cm to 35 cm (and up to 15 cm thick).

2. Shape - typically regular or symmetrical, with orthogonal surfaces, sharp or rounded edges, and other features associated with mass production. Some may be produced with unusual shapes (e.g., “butterfly”) and blend into surrounding terrain.

3. Mass - APL typically weigh from 0.05 to 1.35 kg. ATL typically weigh 1.8 to 13.5 kg.

4. Metallic content - Both ATL and APL can have totally metallic bodies, or can be made with almost no metal content in the entire landmine. The standard specified by the CCW to ensure detectability is 8 grams of ferrous metal. The U.S. refers to its ATL with 2.46 grams of metal as “minimum metal” landmines.

5. Explosive content - ATL contain 0.6 to 11.5 kg of high-nitrogen-content explosives (TNT, RDX, PETN, etc.), and APL contain 0.03 to 2 kg.

6. Resonance signature - a function of the shape, mass, and size of the landmine and its enclosed cavity.

7. Density - relative to the landmine’s environment surrounding.

8. Dielectric constant - relative to the surrounding environment.

9. Electromagnetic signature - across the entire electromagnetic spectrum and relative to the surrounding environment.

10. Gravimetric signature - relative to the surrounding environment.

11. Explosive effluents - Since no current landmine is totally air-tight, trace elements released by the degradation of explosive materials may be detected in the air above a landmine, blend into surface soils, and potentially be absorbed by nearby plants. This release is proportional to local ambient temperatures. High explosives, however, typically have a very low vapor pressure.

12. Deployment - Soil is disturbed when mines are buried, potentially affecting the infrared and reflectivity signature of an area. Surface-laid landmines may present different

signatures from their surrounding environment. APL may also be deployed with metallic and monofilament trip wires.

13. Coatings - Some landmines have painted surfaces intended to help surface-laid mines blend into surrounding terrain. The coloring of plastic landmine bodies is usually integral to the body material.

The study findings below reflect the diversity of feedback received. Where existing non-APL-related devices and systems were suggested by technologists for possible application, discussions focussed on their feasibility for landmine detection (particularly wide-area detection), proposed methods of application, potential modifications needed to suit the new task, and their overall physical characteristics. Where only the underlying technological concepts could be applied, input sought from technologists tended to be mostly theoretical in nature, focussing on the potential applicability of different technologies. Technologists were also encouraged to think creatively and postulate new ways non-APL-detection technologies might be applied or modified to suit the APL wide-area detection mission. Furthermore, when applicable, discussions addressed multiple-sensor systems that might employ data fusion or sensor fusion, as well as the possibilities and constraints for deploying a technology from an aerial platform.

Most suggested approaches for employing the technologies and systems of the different disciplines were highly notional or speculative, but were also grounded in the background and expertise the various specialists brought to bear on the problem. Accordingly, while respondents provided a certain degree of technical background to support their theoretical approaches, no details were offered regarding specific devices, operational parameters, or even potential detection effectiveness.

Table 6-1 below provides a synopsis of Assessment 3 findings. Sections 6.3 through 6.12 provide detailed assessments of the separate disciplines.

## 6.3 GEOLOGY.

**Description of Technologies Employed in this Discipline:**

The principal means that geologist use for scanning or sensing include seismology, gravimetrics, magnetometers, electromagnetic induction sensors, electrical resistivity meters and ground penetrating radar. Most of these technologies are applied to assist oil and other fossil fuel or mineral extraction industries; to predict where and when earthquakes and volcanic eruptions might occur; to monitor underground nuclear explosions; and, in urban areas, to monitor the effects of high levels of vehicle traffic on surface structures.

Seismic technology senses ground vibrations from natural phenomena or man-made explosions, converting physical displacements of the ground into digital signals for manipulation. According to Mr. Bruce Bevin of the Geosight Company, the output of seismic sensors is enhanced with techniques to improve seismic signal-to-noise ratios and digitally stacked wavelets to identify subtle geologic features. Seismic wave propagation is much less reliable close to the surface and varies widely with soil type. Dr. Steven DeVore, a geophysicist with the U.S. Park Service, stated that seismic sensors used to detect phenomena in extremely moist soil can yield data resolutions of down to one to two meters at about 100 hertz, sensing small explosive charges detonated several hundred meters away. When used in loamy soil or soil characterized by rock strata, however, seismic sensors have been unable to detect huge targets such as buried automobiles. Air pockets absorb seismic signals and rock layers distort seismic signals.

**Table 6-1. Synopsis of Assessment 3 findings.**

| DISCIPLINE | REPRESENTATIVE SENSORS | APPLICATIONS | POTENTIAL CONTRIBUTION TO WAD |
|---|---|---|---|
| Geology | Seismometers, gravimetric sensors, magnetometry, EMI, resistivity, GPR | Locating bedrock, underground features/voids, mineral and oil deposits; sensing tremors and nuclear tests; monitoring structure settlement | Poor to Marginal - Discipline addresses very-large-scale sensing, offers no unique detection contribution |
| Remote Sensing | LIDAR, hyperspectral, GPR, side-looking airborne radar (SLAR), IR, all other stand-off sensors | Land-, aerial-, and space-based sensing of man-made and natural phenomena from square-meter to global scale | Good - WAD *is* remote sensing, but discipline offers no unique detection advantages |
| Archeology/ Paleontology | Magnetometry, EMI, resistivity, GPR | Searches for buried bones, building and fossil remains, historical objects | Poor to Marginal - Discipline addresses small areas at a time, requires ground contact or proximity, offers no unique advantages |
| Medicine | Magnetic resonance imaging (MRI), X-ray, tomography, nuclear medicine, ultrasound | Non-intrusive investigation of human and animal tissues and internal organs | Poor - Requires scanned item to be between transmitter and receiver, or direct contact; discipline offers no unique advantages |
| Astrophysics | Optical sensors, SLAR, GPR, hyperspectral, LIDAR | Earth science physics investigates large-scale phenomena on earth's surface (crops, environmental conditions, large man-made structures and movements) | Poor - Discipline requires lower resolution than WAD, offers no unique advantages |
| Drug Sensors | Neutron backscatter, X-ray, thermal neutron activation (TNA), pulsed fast neutron, IR | Close-in detection of metal, non-metal, and organic materials associated with drugs and stand-off detection of drug production | Poor - Requires scanned material to be between transmitter and receiver or very close, or poor stand-off resolution; discipline offers no unique advantages |
| Explosive Sensors | X-ray, TNA, pulsed fast neutron | Detection of explosive materials or components associated with explosive devices | Poor - Requires scanned material to be between transmitter and receiver or very close; discipline offers no unique advantages |
| Non-Destructive Evaluation | All investigated sensors relevant to WAD, plus all other non-invasive proximate or contacting sensors | Investigation of presence or character of subsurface objects or conditions without damaging or consuming area or body surveyed | Marginal to Good - Discipline subsumes many WAD-related technologies but typically requires sensor proximity or contact; discipline offers no unique detection advantages |
| Civil Engineering | GPR, impact-echo, impulse response, spectral analysis of surface waves (SASW) | Search subsurfaces of man-made structures or load-bearing areas for voids, cracks, density changes | Poor to Marginal - Other than GPR, discipline typically requires sensor proximity or contact; discipline offers no unique advantages |
| Cameras | Film-based, CCD, and active pixel sensor visible or IR wavelength sensors; spectral filters | Image collection in visible and IR wavelengths | Poor to Marginal - Mature sensors easily obstructed, potential complement to sensor suite; discipline offers no unique advantages |

Gravimetric sensors measure variations in the earth's gravitational field caused by the changes in density of near-surface objects or voids. Gravimetrics has been used to map bedrock, sense underground caverns, and search for underlying topographic features which could explain surface phenomena. Similarly, magnetometers sense anomalies in the earth's gravitational field caused by the presence of ferro-magnetic materials, and by other flux-distorting influences such as underground utilities and surface vehicles.

Electromagnetic induction sensors measure the electrical conductivity of soil and detect the presence of conductive metals. Such sensors, as discussed in Section 2, are designed for maximum ranges of about three to four meters and usually cannot detect an object any smaller than six centimeters in length. Resistivity sensors emit an active signal of about 40 volts, at from 0.1 to 1 milliohm, to measure non-metallic ground resistance between two conductive rods placed in the earth at about 0.5 meter intervals. Soil penetration of from 0.5 to 2 meters is attainable. Ground penetrating radar systems propagate downward over a variety of bandwidths, sensing for deviations in both the dielectric constant and electrical conductivity of soils caused by the presence of buried objects. GPR technology is capable of detecting nonmetallic objects in soil, but its utility can be limited by soil type and other environmental conditions, such as moisture.

**Application to Wide-Area APL Detection:**

The nature of the necessary equipment, the need for exhaustive preliminary soil analysis, and the spatial resolution attainable by seismic systems are incompatible with wide-area APL detection needs, especially to detect surface-laid mines. Gravimetrics do not sense anything as small as APL and appear to offer no potential for landmine detection. Although many hand-held and vehicle-mounted systems have been developed for geophysical exploration, none of these have any advantages over military detection systems, and are in most cases oriented for point-target detection. Resistivity sensors are not applicable to wide-area detection because of the need for the conductive rods employed therein to be placed close to each other in the ground. Electromagnetic induction sensors and GPR - as deployed in the geologic sciences - are effective in some circumstances but extremely limited in others and offer little novelty to methods discussed in Sections 2 and 3.

The survey also examined other technologies recently introduced into the geologic sciences to detect self-potentials (measurement of moving fluids, heat or ions in the earth); induced polarization (changing the polarity of selected soil objects); radiometry (measuring background ionic radiation in the soil); magnetotellurics (measurement of electrical impedance of subsurface materials); very low frequency radio transmissions (generated by Naval transmitters to communicate with submerged submarines but exploited also to conduct geological surveys); geothermal variations (a function of surface cooling); time domain electromagnetism (to sense sub-surface electromagnetic eddies which can indicate sites of major buried contamination, among many other phenomena); and tomographic surveying. For many reasons, none of these technologies are effective in sensing or discriminating the signatures of typical APL as outlined at the beginning of this report section.

## 6.4 REMOTE SENSING.

**Description of Technologies Employed in this Field:**

Remote sensing encompasses many technologies exploiting the electromagnetic spectrum to sense the atmosphere, land surfaces or sub-surface areas. Remote sensors can acquire images from aerial, space and land-based platforms at rates of from a few hundred square meters a day to hundreds of thousands of square kilometers per day. Because U.S. intelligence and Department of Defense users dominate the field, the most sophisticated and acute capabilities are classified. Only unclassified details, however, were sought from, and provided by, government, academic, and industry specialists interviewed for this study.

The field of remote sensing subsumes the technologies and methodologies of many other fields. Moreover, the stand-off (i.e., wide-area) detection of landmines is actually a form of remote sensing. As a result, remote sensing experts contacted for this study recommended the same technologies for APL WAD as those already being pursued by technologists in the landmine detection field, including hyperspectral imagers (LIDAR), ground penetrating radar, millimeter/microwave radars, and passive infrared sensors (thermal scanners and forward-looking infrared (FLIR) sensors). The unique perspectives of remote sensing technologists were sought, then, on potentially novel applications of these technologies and related devices. To aid in assessing the potential applicability of these technologies, a brief review of their underlying principles is also provided below.

Hyperspectral imaging, such as achieved through Light Detection and Ranging (LIDAR) systems (discussed in Section 2 of this report), involves the use of spectrometers (built around charged coupled devices, or CCDs) to scan frequencies throughout the electromagnetic spectrum for deviations in the wavelengths of energy reflected from soil, vegetation and air samples. According to Dr. Frank Carrier of the TRW Space Center, explosive effluents change the molecular structure of what is being viewed, and its resulting color and thermal image. Commercial LIDAR systems can gather these reflections on visual and near-IR wavelengths. When incoming waves are separated prismatically, a scanner with a differential absorption laser senses changes at specific spectral lines from their normal reflectivity. Data is then assembled in two or three dimensional images. Dr. Dale Hoffman, also at the TRW Space Center, noted that LIDAR can theoretically separate up to 1,000 or more spectral lines at a time. This technology is highly accurate, but is degraded or defeated by vegetation, clouds, and other obscurants. It is presently configured for daylight-only operation.

Ground penetrating radars (GPR) have been used to locate underground objects, evaluate rock/strata formations, and detect underground structures. As outlined in Section 2, GPR can be deployed from both ground and low-flying aerial platforms. Janes International states that GPR systems propagate downward with a high power wave over a variety of bandwidths and sense deviations in both the dielectric constant (permittivity) and electrical conductivity of soils caused by the presence of buried objects, by the disturbance of turned soils, and by the compaction of earth caused by passage of foot and vehicle traffic. GPR systems employ fixed and synthetic aperture antennas, the latter of which is most applicable to wide-area sensing. However, SAR requires extensive data processing to resolve images. As noted earlier, GPR technology is one of the few that might detect plastic objects in the soil.

In addition to GPR, remote sensing experts indicate the possible use of side-looking airborne radars (SLAR) with synthetic apertures (SAR), which project a scalar and polarized wave at a broad angle out to one side of, and downward from, the radar’s forward-moving platform. This wave is then reflected by metal, uneven land surfaces, and resonant cavities, potentially including those in mines. The return signal is received by the SLAR unit and resolved into an image. According to Dr. Saibun Tuatja at the University of Texas/Arlington, SLAR designers face many tradeoffs between trying to attain better penetration at lower frequencies and better resolution at high frequencies. C-band mapping SLAR can penetrate clouds, and perhaps a single layer of tree branches, but has poor resolution. K band aviation SLAR has excellent cloud and fog penetration, but not enough resolution for demining. L-band SLAR can also penetrate clouds and offer good resolution, but has little if any soil penetration, and is seriously troubled by ground and tree-trunk reflectivity.

Passive IR sensors, as discussed earlier, have been adapted to commercial uses over recent years to meet the needs of land planning, agriculture, mineral extraction industries, and especially environmental monitoring. They passively sense variations in the IR emissivity of objects on the ground, then convert input data to video displays. The sensing systems can be packaged in units from 6 to 42 kg for use in small aircraft and satellites, including small UAVs. Forward-looking IR (FLIR) systems are simply thermal scanners that are oriented forward to sense a much broader sweep of terrain. These passive technologies sense and image a thermal return, are somewhat larger and heavier than electro-optical systems, tend to be much more expensive, and are normally mounted in manned aircraft, often with military applications in mind. They are uniquely suited to night or low visibility conditions, but cannot see through heavy clouds or rain. Because solar-heated objects heat up and cool off at different rates depending on their specific heats, both thermal scanners and FLIR are much more effective in the early morning and late evening hours.

**Application to Wide-Area APL Detection:**

Presently, there is no single commercial remote sensing technology or group of technologies that, from a moving aircraft or satellite, can accurately detect surface-laid and buried anti-personnel landmines. Buried background material, such as rocks, and surface materials, like vegetation, provide substantial limitations to the effectiveness of remote sensing technologies. Dr. Joel Davis of Ball Aerospace/USAF Phillips Laboratory explained that remote sensing systems are also limited by their data processing and storage capabilities. The speed and altitude of the sensor, its viewing angle, and the number of spectral collection windows all affect data processing and storage rates and capacities. If continuous input is assumed, Dr. Davis stated, the need for high spatial and spectral resolution can quickly overwhelm today's conventional data storage and processing capabilities. The problem is magnified as the speed and altitude of the sensor, its viewing angle, and the number of spectral collection windows increase. Continuous data from a sensor with a view angle of 9 degrees at 1500 meters altitude in an aircraft moving at 200 knots requires imagery to be digitized and handled at the rate of from $10^{20}$ to $10^{30}$ bytes per second, depending on the degree of resolution, numbers of images processed per second, numbers of systems feeding in simultaneous data, and many other variables. The enormous data acquisition rates for most remote sensing systems mean that at low speed and low altitudes (for example, 5 knots at a height of 50 meters), on-board data storage may be possible, but at higher altitudes and speeds (for example, 200 knots at 500 meters), remote sensing systems will likely require on-board processing.

As discussed in Section 2 of this report, LIDAR imaging and hyperspectral technologies may effectively sense surface phenomena such as soil that is disturbed if mines are buried, and the effect of mine effluents as they leach over time into soils and plants. Nonetheless, as also discussed in Section 2, LIDAR does not provide a through-the-clouds sensing capability. Specialists indicate LIDAR should be able to assess not just visual/near-IR wavelengths, but input from other parts of the energy spectrum as well. They also state LIDAR currently offers potential for daylight use and might later support integrated radar and other inputs.

According to Dr. Davis, LIDAR scanners can recognize thermal differences of below $0.1^{o}$ Kelvin, and comparable levels of light wavelength. A satellite LIDAR sensor at 200 km with a 1 meter footprint with a 1 milliamp CCD can sense about $10^{-11}$ watts per square meter in soil reflectivity, although there are many variables in this calculus, including imagery resolution, CCD sensitivity, and light gathering capabilities of the viewing device. The Environmental Research Institute of Michigan has applied this technology to sense deviations in the reflectivity of soils caused by the presence of hydrocarbons, heavy metals and other pollutants. Dr. Narasimha Prasad, of the private firm Optical Engineering, stated that others are using LIDAR to monitor the integrity of the Alaska Pipeline and to sense insect infestations in commercial cotton and soybean crops. Mr. Robert Horvath, of the firm ERIM, stated that, depending on the front-end optics and data acquisition rates, the reflectivity of plants about 0.1 m across in a 1 meter wide footprint at 1000 m altitude can be sensed; but why plants are being stressed (i.e. from drought, pollutants or other causes) cannot yet be predicted. Mr. Horvath also noted that sensing the effects of mine effluents on soils might thus be more useful than trying to sense their effects on plants. Dr. Barry Rock at the University of New Hampshire said it is not known if hyperspectral sensors from remote platforms could also detect molecular changes in surface air samples from buried mines, but he noted that it seems unlikely.

Mr. Gary Clark of Ball Aerospace stated that on-board power requirements for laser scanners, and for various computing systems to process the resulting data, appear within the normal capabilities of aerial and satellite platforms, and may well be adaptable to small unmanned aerial vehicles. Additionally, widening the viewing angle of the visible/IR devices may be possible to increase the speed of an aerial demining survey, but will require more on-board data storage and processing power. Filters may help clarify the image being scanned to reduce atmospheric effects. Also, it is not clear how many more lines of input light can be scanned by LIDARs to improve image resolution, or in what dimensional array they should be imaged for demining. Widening the spectrum of input and changing the angle of light sensed, either through use of multiple sensors or integrating images from a moving sensor, should offer a higher degree of sensitivity. The spectrum being scanned can also be increased by adding more sensors. TRW has linked hundreds of them in various different arrays for satellite uses.

GPR is able to investigate into the ground, but its penetration varies enormously with soil type, moisture content, transmitted power, and other characteristics. Mr. Harvey Miller, of Autometric, Inc., says that penetration of 20 meters has been demonstrated in dry sand (an electromagnetically benign medium), but may be limited to less than one millimeter in other soils, depending on soil moisture content. Dr. Farouk El Baz, at the Boston University Center for Remote Sensing, also noted that Egyptologists using synthetic imaging radar (SIR) operating in the 90 MHZ to 1.2 GHz range aboard the NASA Space Shuttle have looked over 10 meters deep into Sahara soils with a resolution of 8 to 12 meters to locate ancient watercourses and roads. In addition, the US Geodetic Service (part of NOAA) in Boulder, CO, also owns the rights to a unique "sounder" technology, which can emit pulses in the energy spectrum gap from 300 KHz to 30 MHZ, i.e., between the ranges of EM sensors and ground penetrating radars. Dr. William Hanna of the USGS indicated that the lower frequency range should enable through-the-ground ranges of over 10 m. However, its capability to sense targets such as mines has not been tested. Overall, remote sensing technologists noted that the best tradeoffs of height, power, resolution, bandwidth, and frequency are still being explored and are not known for landmine detection.

Technologists at the Folsom Research Institute postulate that input from a moderately low frequency, high bandwidth radar, passed through a real-time synthetic aperture processor and integrated with parallel inputs from video and infrared sensors, should be able to identify buried mines from aircraft. They have proposed a swept-frequency GPR with wide synthetic aperture for the natural gas industry that, when linked with tapered acoustic-burst sonic waves from ground transducers, would locate and identify plastic pipes as small as 1 cm in diameter through about 15 cm of soil. Preliminary field tests by the Army

Research Laboratory (ARL) tend to confirm the feasibility of this approach. The ARL approach presumes a side-looking, boom-mounted radar (described earlier in Section 5). However, it should be noted that the linear image of even a thin pipe is much more readily discriminated from surrounding terrain than a landmine might be.

SLAR systems face performance impediments similar to those of GPR and typically achieve much less ground penetration. According to the USGS' Dr. Hanna, commercial SLAR systems have not demonstrated any consistent capability to penetrate more than about 2 cm of earth, due to the linear attenuation of radar energy as it passes through air, the low transmissibility of electromagnetic energy from air to soil, and the rapid absorption of energy in typical SLAR frequencies by soil moisture, especially in clay. Research is underway to improve penetration by increasing the power and bandwidth of the transmitted wave, altering its polarity, focusing the radar beam, lowering frequencies, reducing air distances, and other means that enable ground-penetrating radars to penetrate soil. Widening the synthetic aperture improves soil penetration somewhat and improves spatial resolution greatly. Radar reflection is imaged in several formats, including three-dimensional stereoscopic imaging, which might help sense the depth and shapes of mines.

The exact depth to which SLAR systems could potentially penetrate soil is not known. One researcher claimed that under ideal conditions in dry sand, penetration to a depth of over 3 meters should theoretically be possible. However, Dr. John Hanson, of the TEC Research Institute, said that recent TEC tests of SLAR under just such conditions, using X, C and L-band from 2400 meter and 4800 meter altitudes, could not detect any buried mines. With the longer wave L-band radar, TEC was able to identify soil that had been disturbed where the mines had been buried but, when gain was increased, greater background "noise" drowned all useful signals.

The range and soil penetration of SLAR systems are also a function of transmitted power, which may exceed the capabilities of small platforms and perhaps satellites. Swept-wave microwave transmitters may offer higher resolution than stepped frequency transmitters. According to Mr. Lester O'Leary, of Janes International, vertically polarized transmissions are clearly superior for detecting subsurface objects, while horizontally polarized waves give a better return from surface objects.

High resolution synthetic aperture SLAR may also be able to produce unique signatures to identify specific types of mines. Higher radar frequencies reflect from the angular edges of regularly shaped objects, and lower frequencies from the center of such objects. Dr. Steven Knapp at the Folsom Research Institute noted that, if tuned filters were then developed, high resolution systems might be able to sense and image differential signatures, and compare them to a database of known shapes to identify specific types and classes of mines. This would require the population of a signature database for the widest variety of soils, mines and clutter.

Despite their highly limited ability to penetrate earth, commercial SLAR may eventually detect objects as small as a few centimeters in size, at or above the surface. Dr. Brooks Elwood, at the University of Texas/Arlington, noted that objects of about 5 centimeters in diameter on or flush with the surface cannot be sensed with current SLAR from altitudes of about 1500 m, but might be detectible from about 100 m.

Regarding radar systems overall, remote sensing technologists indicate GPR offers a feasible component for a multi-sensor array for ground vehicle and helicopter use, and may be more suited to locating individual mines than minefields. The capability to sense the presence of plastic in the soil, when integrated with the capability of SLAR and hyperspectral imagers to recognize very small regular shapes, might help to sense small plastic APL, a particularly difficult component of the demining problem. Moreover, while GPR in general has been developed to look downward, Mr. Harvey Miller of Autometric stated that for demining applications, they would have to be optimized to scan more laterally. Finally, as noted in Section 2, fixed-wing and helicopter-mounted GPR, still being developed, offer a much more efficient system than ground-emplaced transducers to transmit radar pulses into the ground over wide areas.

If radar-based imaging systems are to eventually be able to precisely locate and image individual mines, they will require GPS much more precise than military systems now accurate to 16 m, and civil systems now accurate to 32 m. Folsom Research Institute and SRI International are developing a carrier-wave phased GPS system with a synthetic aperture of many miles to locate objects to within one foot. Others developing highly accurate differential carrier phase GPS include the U.S. Geodetic Service office and the Aztec Corporation.

The resolution capable through FLIR systems depends on altitude, processing speed, light/IR gathering capability, and other variables. Dr. Fred Caristo of George Washington University pointed out that the greatest difficulty associated with FLIR systems, however, has been an inability to develop the high spatial resolution needed to sense individual mines. Dr. Davis at Phillips Laboratory indicates that better processing might well be able to solve the problem in passive IR. Research with such systems as NASA's Thermal Imaging Multispectral Sensor (TIMS), when flown at low altitudes, has shown potential for detecting minute relative thermal differences between surface objects, but spatial resolution has to be traded off for additional area coverage. Overall, the real potential of FLIR systems would be to sense the earth disturbed where mines have been buried, not the mines themselves.

## 6.5 ARCHEOLOGY/PALEONTOLOGY.

**Description of Technologies Employed in this Discipline:**

Archeologists and paleontologists employ technology for scanning small pieces of terrain to depths of one to five meters in search of buried bones, graves, fossil remains, building foundations, and other objects of historical interest. According to Dr. Elwood at the University of Texas/Arlington, there are four key sensing or scanning technologies employed in archeology and paleontology: magnetometers, resistivity sensors, electromagnetic induction sensors, and ground penetrating radars (GPR).

As explained in Section 2, magnetometers passively sense deviations in the earth’s magnetic field caused by the presence of objects in the soil, especially metals, to a resolution of about nine square centimeters. According to the Geosight Company’s Mr. Bruce Bevin, the area scanned by most hand-held magnetometers is typically no larger than 0.125 meters by 0.5 meters in size. Soil penetration to a depth of 0.5 meters is possible, depending on the size of the target.

As mentioned above in the discussion on geology, resistivity systems are used to transmit electrical current into the earth. Sensors then measure the non-metallic ground resistance between two conductive rods placed in the earth.

Electromagnetic induction sensors measure the electrical conductivity of soil, are hypersensitive to the presence of conductive metals, and are the basis for most hand-held military and commercial “mine detectors." These devices consist of one or two conductivity measuring loops. As noted in Section 2, electromagnetic induction sensors face a tradeoff between sensing small objects and sensing deeply buried objects. According to Dr. Don Heimmer, of the private firm Georecovery Systems, those devices designed for maximum ranges of about three to four meters usually cannot detect an object any smaller than six centimeters in length.

Ground penetrating radar for archeological and paleontological use operates at somewhat lower frequencies and has slightly better resolution than above-the-ground radars, but are severely limited by soil type. As discussed earlier in this section, GPR technology faces tradeoffs between image resolution and penetration depth.

**Application to Wide-Area APL Detection:**

Although some of the technologies described above have been used to locate Civil War-era and other buried unexploded ordnance, such surveys involved scanning only a few square meters of ground at a time. The scale of these investigations suggest that methods and tools employed in archeology or paleontology have limited applicability to wide-area APL detection for humanitarian demining, but may be applicable in the locating and clearing of individual mines. Since archeology and paleontology are not traditionally high-tech fields, none of the systems presently utilized in these fields reflect the most advanced technologies.

## 6.6 MEDICINE.

**Description of Technologies Employed in this Discipline:**

Technologies employed in medical diagnostic imaging cover a variety of areas, including magnetic resonance imaging, x-ray, tomography, nuclear medicine, and ultrasound. Most of these are mature technologies.

Magnetic resonance imaging (MRI) employs a static magnetic field, a gradient magnetic field, and a radio frequency coil to transmit and receive signals. MRI produces "sliced" images of the human body from between two to ten millimeters in thickness that may be viewed along a variety of axis and can be used to construct three-dimensional images.

X-ray imaging is perhaps the most familiar of all medical diagnostic imaging techniques. This technology involves transmitting x-rays from a radioactive isotope through human tissue and onto a film panel receiver.

Tomography is less a technology *per se* than it is a methodology for manipulating the two-dimensional data collected from other technologies into three-dimensional views.

Nuclear medicine typically involves injecting a harmless radioactive dye into the body of a patient, and then scanning the patient with a camera-like device to determine the flow pattern of the dye through the patient's body.

Ultrasound is the only technology currently used in medical imaging that is reflective. A transducer emits a high frequency sound wave and simultaneously measures the portion of the wave that is reflected back off of human tissue, allowing health care professionals to image human tissue in real time. Ultrasound is currently used in cardiology, radiology, obstetrics, and gynecology, and its clinical uses continue to grow. Most ultrasound systems are digital table-top, portable units. Resolution and color sensitivity vary across ultrasound devices. The ease of using ultrasound is based on the fact that the scanned object does not need to be positioned between a transmitter and a separate receiver.

**Application to Wide-Area APL Detection:**

As pointed out by Ms. Cari Kesseol at the Alexandria Association of Radiologists, Mr. Joe Lewelling at the Association for Advanced Medical Instrumentation, and Mr. Bob Britain at the National Electrical Manufacturers Association, most of the medical imaging technologies outlined above require that the scanned object be located between a transmitter and a separate receiver. For detecting APL close-in or from standoff distances, this limiting factor means that most medical imaging technologies are ill-suited for application to APL detection.

Ultrasound is the only medical technology that does not feature this shortcoming. Mr. Dennis Meister at Acuson Corporation, Mr. Don Plante at Picker International, and Mr. Dale Leach at Toshiba each explained that by employing a transducer that both sends and receives the high frequency ultrasonic wave emissions, there is no need to place the object in question between a receiver and a separate transmitter. Nonetheless, because ultrasonic wavelengths are so short and because air molecules are spread relatively far apart, ultrasound waves cannot effectively travel through air. The transducer must therefore be coupled directly against the object being scanned. As Mr. Graham Thursk at Advanced Technology Laboratories, Inc., pointed out, without a coupling mechanism, ultrasound technology does not appear applicable to wide-area detection of APL. Mr. Meister of Acuson indicated that sensors might be embedded in ground spikes, but would need to surround a suspected mine within a radius of only one meter due to poor resolution.

Mr. Meister also noted that it would be very difficult to discriminate mines from rocks using ultrasonic technologies. He stated that ultrasonic technology works best in fluid medium, and that it may be best to flood the area being scanned. However, he also said that soil inclusions such as rocks, roots, plant matter, urban debris, and even gas bubbles reflect ultrasonic waves as well as mines, so it would be difficult to obtain a reliable pattern for discrimination.

## 6.7 ASTROPHYSICS.

**Description of Technologies Employed in this Discipline:**

Astrophysics includes the subfields of astronomy and solar physics, extraterrestrial physics, and earth science physics. Of these subfields, only the last has scanning or sensing technologies of relevance to APL demining. They include optical technologies, SLAR, GPR, hyperspectral imaging, and lasers, the general characteristics of which are described in Section 2 of this report and in the remote sensing discussion above (Section 6.4). As with other disciplines that employ radar systems, data storage and processing requirements present major challenges and limitations. Additionally, since the very lowest satellite orbits are at altitudes of about 200 km, all of the space-based real-aperture viewing and sensing systems used by the National Aeronautics and Space Administration (NASA) tend to have poor resolution. For example, NASA’s multispectral crop infestation imagers and SLAR topographic sensors measure areas of Earth’s surface in hundreds of meters.

Even synthetic aperture GPR loses resolution from similar space-based distances. The resolution of such systems is no better than about 5 meters, although penetration of desert soils can exceed 20 m and has enabled systems on the Space Shuttle to locate ancient cultural sites in the Sahara Desert. Laser altimeters are not used as sensing systems *per se*, but can provide better resolution. At 200 km, their resolution is about 1 meter. These altimeters have been used to detect vertical displacements of less than one meter in the tops of Icelandic volcanoes expected to erupt. Optical resolutions of from 1-2 meters are also available in the U.S. and French LANDSAT systems.

**Application to Wide-Area APL Detection:**

As noted in Sections 2 and 3 of this report, ground-penetrating radar systems and LIDAR systems all face challenges in detecting APL imposed by soil type, resolution requirements, penetration requirements, and weather conditions. Moreover, the technologies and systems used in astrophysics are designed to detect large phenomena; resolution does not present nearly the same problems in astrophysics as it does in APL detection. NASA engineers at the Goddard Space Center noted that higher resolutions might be possible from commercial systems, but they have not been developed because there has heretofore been no need to do so.

## 6.8 DRUG SENSORS.

**Description of Technologies Employed in this Discipline:**

Technologies employed in drug detection (ranging from normal pharmaceutical applications to scenarios involving illicit drugs) focus on nuclear analysis for its ability to image metallic, nonmetallic, and organic materials. Nuclear analysis is highly penetrating, non-intrusive, and can be conducted in real-time. Methods of nuclear analysis include neutron backscatter techniques, x-ray imaging, thermal neutron analysis, and pulsed fast neutron analysis. Although certain of these methods, such as x-ray imaging, are extremely mature, others, such as pulsed fast neutron analysis, are the products of more recent scientific inquiry.

The Drug Enforcement Agency (DEA), although unwilling to comment publicly, is widely believed to employ infrared technologies in conducting wide-area searches for illicit drug production sites. For these purposes, the DEA is less concerned about identifying specific elements or scanning particular containers and more focused on locating high levels of activity in illicit production or refinement sites. Infrared technology is relatively mature, although its inherent limitations may limit its applicability, as seen below.

Neutron backscatter involves scanning an object by emitting low level radiation from a transmitter at close proximity. The type and intensity of the radiation reflected back by different materials in or around an object is then measured and used to create an image.

Traditional x-ray imaging is similar to that performed in medical diagnostic imaging. The object to be scanned must be placed between the transmitter and a photographic plate or receiver that measures the radiation and is used to create an image.

Thermal neutron analysis involves using an isotopic or electronic source of neutrons that are reduced in energy (also known as *thermalized*) and then emitted toward the object to be scanned. The thermalized neutrons interact with the elemental ingredients of the object being scanned and subsequently emit gamma rays whose energies are uniquely characteristic of different elements. The gamma rays are measured, allowing operators to determine the types and amounts of different elements present in the object being scanned.

Pulsed fast neutron analysis involves creating fast neutrons via a nuclear reaction. Such neutrons are highly penetrating and excite the nuclei of the elemental ingredients of the object being scanned. These excited nuclei then emit characteristic gamma rays. The time between the creation of the fast neutron and the emission of the gamma rays is measured, allowing operators to deduce relative positions of elements within an object being scanned. Images of the elements within the object are then created.

**Application to Wide-Area APL Detection:**

Nuclear methods of analysis have been proven to be extremely capable of scanning through a variety of substances to detect metallic, nonmetallic, and organic materials. However, as described in information from American Science and Engineering, Inc., all of the nuclear methods of analysis described above require that the scanned object lie between a transmitter and a receiver. Additionally, in order to attain proper signal strength, transmitters for nuclear methods of analysis need to be located close to the object being scanned. These constraints render nuclear methods unfeasible for standoff, wide-area detection of APL.

Infrared detection, as is likely used by the DEA in performing wide-area searches for illicit drug production sites, appears to have clear applicability to APL detection. Infrared scanners can measure differences in temperature between ground that is undisturbed and ground under which an APL has recently been emplaced. The thermal effects of ground disturbance, however, are limited in duration. Moreover, infrared scanners only work in favorable weather conditions. Thus, while potentially applicable, infrared technologies would not offer a complete solution for wide-area detection.

## 6.9 EXPLOSIVE SENSORS.

**Description of Technologies Employed in this Discipline:**

Technologies used in explosive detection are very similar to those used in drug detection. As in drug detection, nuclear methods of analysis are employed most often in explosives detection because of their ability to image metallic, nonmetallic, and organic materials. Unlike drug detection, however, explosive detection methodologies most often rely upon x-ray imaging—an extremely mature and reliable technology.

Traditional x-ray imaging is similar to that performed in medical diagnostic imaging. The object to be scanned must be placed between the transmitter and a photographic plate or receiver that measures the radiation and is used to create an image. Without access to all sides of an object to be scanned, reliability of detection is substantially reduced.

Although used less frequently, thermal neutron analysis and pulsed fast neutron analysis have also been applied to explosives detection for their ability to specifically identify explosive compounds. Thermal neutron analysis involves emitting reduced-energy neutrons toward the object to be scanned. As the neutrons interact with the elemental ingredients of that object, gamma rays whose energies are uniquely characteristic of different elements are subsequently emitted. These gamma rays are measured, allowing operators to determine the chemical makeup of any explosive compounds present in the object being scanned.

Pulsed fast neutron analysis involves creating fast neutrons via a nuclear reaction. These neutrons are emitted toward the object to be scanned, exciting the nuclei of the elemental ingredients contained therein. These excited nuclei then emit characteristic gamma rays. The time between the creation of the fast neutron and the emission of the unique gamma rays is measured, allowing operators to deduce the types and relative positions of elements within an object being scanned. Images of the elements within the object are then created.

**Application to Wide-Area APL Detection:**

Officials at the U.S. Postal Service noted that nuclear methods of analysis have been proven to be extremely capable of scanning through a variety of substances to detect metallic, nonmetallic, and organic materials. But, as noted by Ms. Gwen Caudle and Mr. Edward Kittel at the Federal Aviation Administration, the object being scanned must be located between a transmitter and a receiver. This limitation would prove prohibitive in wide-area APL detection applications.

Moreover, transmitters for these methodologies must be located close to the object being scanned in order to achieve proper signal strength. Therefore, according to Mr. Silvair Shimoni and Mr. Fred Roder of InVision Technologies, these methods would not be applicable for standoff, wide-area detection of APL.

## 6.10 NON-DESTRUCTIVE EVALUATION.

**Description of Technologies Employed in this Discipline:**

In the field of non-destructive evaluation (NDE) and the related fields of non-destructive testing (NDT) and non-destructive investigation (NDI), the presence and character of sub-surface objects and conditions are investigated without damaging, deforming, or otherwise consuming the area or object in question. Like remote sensing, and encompassing the widest array of applications, it subsumes those technologies used in nearly all the other disciplines in this report section, as well as those typically associated with landmine detection. Queries were made of technologists who specialize in non-destructive evaluation, testing, and investigation (treated similarly for purposes of this study) to determine the existence or possibility of any unique or untried approaches to landmine detection.

**Application of Technologies to Wide-Area Detection:**

None of the NDE experts contacted could specify technologies that might be immediately transferable to the wide-area landmine detection mission. Highly notional or speculative approaches were offered, though grounded in the background and expertise these specialists brought to bear on the problem. However, no specifics were offered regarding particular devices, potential detection effectiveness, or even operational parameters.

Terry Phillips, of Los Alamos National Laboratory’s (LANL) Engineering Science and Applications Division, Non-Destructive Evaluation Team, suggested the use of ultrasonic technologies, in which high frequency sound waves are induced through a medium and the reflected returns are interpreted. He stated that, while this technology is commonly used commercially to detect buried pipes, it typically requires a direct coupling (i.e., contact) between the detector and the ground. This coupling renders it less desirable for landmine detection. Moreover, he noted that pipes are readily recognized by their linear shape, whereas mines might not be so easily distinguished from rocks and other objects similar in size and shape to a landmine. These findings reflect similar insights from experts in other disciplines.

Tom Claytor, also of the LANL Non-Destructive Evaluation Team, cited thermal neutron activation (TNA) technology, which has already been studied for landmine detection, as a possible NDT candidate technology. However, he noted that TNA has a very short stand-off range and would therefore not be applicable for wide-area detection. A pulsed neutron approach was also cited, although it, too, suffers from range limitations as well as unit size - its biological shielding (to protect humans against radiation) adds prohibitive weight.

Mr. Claytor also suggested the applicability of infrared detectors, including dual-band units, and recognized them for the role they already play in the landmine detection field. He also described as well an existing approach in which LIDAR is employed to search for the out-gassing emissions from landmines on a hot day. He said the device would have to be tuned to detect the appropriate IR absorption bands, which would require the characterization of those emissions sought. Finally, Mr. Claytor noted that explosive materials are often like tar in consistency and highly damped, and therefore can be difficult to detect acoustically.

Mr. Chris Furtunko, of the National Institute of Standards and Technology's (NIST) Materials Reliability Office in Boulder, Colorado, proposed "painting" the ground with microwave emissions, causing differential heating and cooling of buried items with different specific heats. The resultant temperature differences could then be sensed in a manner already employed for landmine detection, using infrared or millimeter-wave detectors to locate the objects.

Mr. Furtunko agreed with other technologists that it would be difficult to discriminate buried items using ultrasound. He did suggest one approach in which a few different low-energy, anti-disturbance detonators might be used to quickly induce a few ergs of energy into the ground, providing a low-frequency ultrasound source in the 40-50 kHz range. The interpretation of return signals picked up by a transducer might indicate what was buried in an area. However, this would require contact between the transducer and the ground, since a stand-off approach would likely result in too much reflection from the air/ground interface. Also, the signals of buried objects would have to be discriminated by adaptive means (i.e., signal processing) by assessing contrasts contextually. It was proposed that such transducers could be deployed with "spider" robots. These robots, which would have to be light weight and very inexpensive, might move across an area and deploy a probe that could transmit the signal, receive its reflection (return signal), and determine the local soil stiffness. This is similar to the approach seismologists use, except that the signal is produced by a moving truck and the return is detected with a microphone or a line of geophones.

Mr. Furtunko also proposed another approach in which ultrasound is transmitted into the ground and the return (response at the surface) sensed with a laser. Resonance signatures associated with buried man-made objects would be sought. This approach requires equating the mine/ground interaction to a mass/spring system. The ground could be swept with different frequencies to discriminate the different signatures and therefore possibly rocks from mines. However, ground contact again is preferred for ultrasound sensor applications, rendering this approach less desirable for landmine detection in general and unfeasible for wide-area detection.

Mr. Furtunko indicated that the technology underlying resident mechanical spectroscopy (RMS), which has proven very effective for inspecting the honeycomb substructure of aircraft wings, might be applied to landmine detection. This approach requires the movement of an ultrasound source across the inspected area, the detection of the return signals, and the construction of a three-dimensional image of the underlying area. A sweep of the signal across the spectrum would permit the discrimination of different items' signatures. For landmine detection, it was proposed that many light-weight, inexpensive "spider" robots could be deployed, moving in a coordinated manner across an area, each scanning their respective coordinates. While RMS technology has been around for 30-40 years, it requires extensive data processing and has therefore become more accessible and feasible only with recent improvements in computational abilities. It was proposed to use vibrations low enough to detect buried landmines but not low or energetic enough to cause detonations. This approach has been used effectively in controlled conditions to detect motion down to one Angstrom, and the device sensor only costs about $100. As with the other approaches, the drawbacks herein include the required contact between sensor and ground, the availability and functionality of inexpensive "spider" robots, the potential for those robots to detonate land mines, the data processing and image generation, and the accurate interpretation of images created. Mr. Furtunko did not indicate how these approaches might be modified for wide-area detection.

## 6.11 CIVIL ENGINEERING.

**Description of Technologies Employed in this Discipline:**

Civil engineers commonly employ ground-penetrating devices to investigate the condition of subsurfaces of, or inaccessible areas within, pavements, soils, poured concrete, bedrock, structural members, and other potential load-bearing systems. They search for large voids that could indicate weakened discontinuities in concrete; density changes that could indicate bedrock, mineral veins, or water intrusion; or small cracks in structural steel. The field of civil engineering has used and advanced the state of such technologies as ground-penetrating radar; impact-echo (IE) devices, with which the echo return of an acoustic signal is electronically sensed and interpreted for subsurface conditions; impulse response, in which the energy of reflected low-frequency acoustic waves created by a surface-level impact is interpreted to determine the presence of voids and the damping ratio of underground materials; and spectral analysis of surface waves (SASW), where measurement of the velocity of surface shear waves allows determination of soil elastic moduli and sub-pavement layer profiles. Of these approaches, all but GPR require direct sensor coupling with the ground and the use of a mechanically energetic signal (e.g., acoustic generator or ground impact), neither of which is desirable in landmine detection.

**Application of Technologies to Wide-Area Detection:**

All of the civil engineering technologists spoken with cited the on-going research into GPR use for landmine detection. However, none could specify any other technologies that might be immediately transferable to the wide-area landmine detection mission. Only notional approaches to detecting landmines were offered, founded on the different experts' knowledge of civil engineering sensor technologies.

Mr. Don Alexander, of the Pavement Systems Division at the Army Corps of Engineers' Waterways Experiment Station, Vicksburg, Mississippi, noted that ground penetrating radar is probably the best technology for doing wide-area searches, but said the return signals are difficult to interpret, especially those caused by smaller buried objects. He cited a major program that was undertaken about 10 years ago to develop a helicopter-mounted aerial landmine detection system that employed many different sensors and much software work. However, he indicated the effort did not result in a viable end product.

Dr. Kenneth Stokoe, of the Civil Engineering Department in the University of Texas at Austin, is a former Chairman of the American Society of Civil Engineering's Geophysics Committee. He cited a project funded by the U.S. Navy in which his CE department's Applied Research Laboratory is investigating whether resonances can be excited within the soil without ground contact, allowing the differentiation of buried objects from the soil itself. Dr. Stokoe did not indicate what the results of this work have been to date.

Upon considering the landmine detection problem, Dr. Stokoe conceptualized an approach in which the ground might be subject to acoustic loading, such as from the beating down draft of a helicopter. He suggested a buried landmine might be excited into a low-frequency rocking motion from lateral forces or, if sensed directly from above, with a vertical excitation. He noted that this approach, however, could be negated by the dampening effects of ground cover, although an accompanying foliage-penetrating radar might also be employed to compensate for that possibility.

Expanding on this approach, Dr. Stokoe suggested that water might also be dumped on the ground from a helicopter-borne sprayer to create a ground cover that reflects radar. Again using the helicopter as an acoustic wave source, reflections in the water might then be assessed using a ground-penetrating radar. The GPR would be swept in a well-traced arc, perhaps 10 feet by 10 feet per second. Minor reflections in the water's surface could then be examined for the resonance signatures of specific buried objects. Additionally, a sensor deployed at the back of the helicopter and oriented to detect and interpret reflected surface (Rayleigh) waves might be used in a complimentary sensor fusion mode to obtain a more complete image of sensed objects. This feature might be particularly effective for inclined (i.e., tilted) landmines.

It was also noted that the migration of water on the ground's surface would be affected by buried objects. Exploiting this property might indicate or confirm the suspected presence of landmines. For example, in a clay soil area, water would move towards a pooling area above the buried mine, whereas it would flow away from a mine buried in permeable sand. However, this would require characterizing the soil to interpret the water movement.

A specific concern regarding either of the above two approaches is the potentially rapid and uneven absorption of the water into the ground due to non-uniform soil consistency, roots, animal burrows, or other discontinuities.

Dr. Mary Sansalone, of Cornell University's Civil Engineering Department, emphasized that stress waves, such as those induced in the ground with an acoustic source, reflect almost entirely at the air/ground interface due to the different media stiffnesses. This renders detecting acoustic waves from a standoff position very difficult, if not impossible. Dr. Sansalone also stated that, while water will amplify vertical ground movements, it will not transfer shear waves. This supports the idea of reading vertical ground movements in a surface water layer but diminishes the notion of reading surface waves.

## 6.12 CAMERAS.

**Description of Technologies Employed in this Discipline:**

Most of the technologies employed in cameras involve either the visible light or infrared portions of the electromagnetic spectrum. Visible light cameras usually use the sun as an illumination source, recording the reflection and absorption properties of an object being observed. Visible light cameras record these images on photographic film or in digital form. Despite their versatility and maturity, visible light cameras are limited in the same ways in which human vision is limited—they are less effective in poor lighting conditions, have difficulty distinguishing an object when it is surrounded by other objects of similar color and texture, and are not very effective in poor weather conditions.

Infrared cameras measure and record on photographic film or in digital form the thermal signatures of objects. Differences between the spectral signature and texture of soil disturbed during mine emplacement and that of surrounding soil, and between the temperature of an object and its surroundings, result in different photon emission levels. Infrared cameras detect and differentiate these photons. Without adequate contrast between an object and its surroundings, however, infrared cameras are of little use. Weather conditions and time of day are critical in achieving sufficient contrast.

**Application to Wide-Area APL Detection:**

Information collected from Eastman Kodak and Compix indicated that technologies used in cameras have only very limited use in the detection of APL. Proper weather and lighting requirements severely limit the usefulness of visible light technologies in detecting surface APL. More importantly, visible light technologies are of no use in detecting buried APL.

Infrared camera technologies, however, have direct applicability to wide-area APL detection. Infrared cameras, such as those developed by Kodak and Compix, can measure differences in temperature between recently disturbed ground - where an APL has been buried - and the surrounding, undisturbed ground. According to Mr. Roland Simmons of Kodak, there are, however, major limitations in using infrared cameras to detect APL. For instance, the thermal effects of ground disturbance are limited in duration. Additionally, infrared cameras only work in the most ideal of weather conditions. Thus, while potentially helpful, infrared technologies appear to offer only a partial solution for the wide-area detection of APL.

# SECTION 7

# CONCLUSIONS

## 7.1 GENERAL.

In Assessment 1, a literature search was performed for technologies and systems applicable to the wide-area detection of landmines. While that search identified many potentially promising RDT&E efforts, none currently appeared to provide a complete solution for WAD. However, some of those efforts, which included both single- and multiple-technology approaches, appeared to offer greater potential for the wide-area detection mission. DSWA therefore requested a follow-up Assessment 2, in which select systems and the activities of certain developers were more thoroughly investigated. DSWA also requested an Assessment 3, in which other fields not normally associated with landmine detection were investigated for the contribution they might make to the wide-area detection of landmines.

No complete solution to the wide-area detection (WAD) requirement was found in any of these assessments. None of the systems investigated is assessed as likely to provide a reliable, accurate, fielded solution to APL WAD in the near-term (0-2 years) or mid-term (2-5 years). In addition, because each of the systems is at a different level of development, and because no performance-based requirement for either monitoring an APL ban or humanitarian demining has been promulgated against which these systems can be designed or evaluated (see Section 7.5 below), it is difficult to project the likely time frame in which they might achieve acceptable performance. A period of up to 2 years is postulated as necessary for the formulation of validated, agreed-upon, performance-based requirements; determination of a technical approach for system development from concept to production; and development of a program plan and funding profile.

Differing degrees of functionality were found in the application of various individual technologies, each of which may provide a partial solution. Multiple-technology systems, as currently applied or under consideration, will likely offer improvements over single sensors by leveraging the strengths and compensating for the limitations of the individual technologies. Moreover, developers note that single sensors have higher false alarm rates and that the landmine detection development community endorses the development of multiple sensor systems.[1] This assessment effort also found that, while there is considerable experience with sensor technologies in disciplines not normally associated with landmine detection, those fields investigated offered no unique or promising technologies or solutions to the WAD mission.

A number of recurrent issues were identified regarding the various sensors and systems investigated, driven mainly by the underlying physics of the technologies and application scenarios. Predominant for all detection systems is the difficulty in discriminating landmines from surrounding clutter. The magnitude of this issue led DARPA to undertake a preliminary study aimed exclusively at recognizing and characterizing background clutter. Further work in this area appears warranted. Another important issue encountered is the need for accurately marking (mapping) the location of mines and minefields, both for avoidance and for removal or destruction. Several developers described their attempts at marking, but, in addition to better spatial resolution, it appears many systems would greatly benefit from improvements in locational precision. This also appears to be an engineering-level problem, not one of basic research and development.

Other recurrent issues include: environmental interference, such as the obstruction of LIDAR and visual and IR sensors by clouds or foliage; trade-offs between penetration and resolution, such as with ground-penetrating radar in different soil types; target imaging and identification, because automatic target recognition requires a database of all possible targets in the widest range of search environments for the sensor type(s) employed, and manual identification requires adequately interpretable imagery; and potentially very large data processing and storage requirements. These and related issues must be resolved to achieve a viable detection system.

While this study was intended to focus on select wide-area landmine detection RDT&E efforts, other technology development initiatives were identified during the course of the study, including five multi-university research initiatives (MURIs) sponsored by DoD and research efforts presented at numerous technical fora (including SPIE '97 and other conferences).

## 7.2 SUMMARY OF FINDINGS ON SPECIFIC SYSTEMS.

In Assessment 2, a more focussed assessment was performed on seven of the systems identified in Assessment 1 as most viable for WAD. This follow-on assessment included direct contact with, and interviews of, the systems' developers, including site visits. In addition, LLNL's MIR and DoD's ASTAMIDS were investigated further to ascertain their potential applicability to WAD.

Of the RDT&E efforts investigated in the follow-up assessment, no single- or multiple-technology approach currently provides a full solution to the broad array of possible WAD scenarios, although a few of the most promising systems warrant continued monitoring. Multi-sensor approaches appear more likely to eventually yield solutions than single sensors, but the greater complexity and data processing requirements of combining multiple sensors add their own unique RDT&E burdens. It was found that the physical limitations inherent in the individual technologies manifest themselves in the different systems that employ them, including, but not limited to: the reflection of GPR at an air/ground interface, the environmental obstruction of passive IR imaging, and the speckle of active IR laser reflections. Moreover, as mentioned above, all technologies are challenged by image interpretation requirements and by the requirement for discrimination of mines from clutter. Those technologies that may offer the nearest-term promise are discussed in Section 7.4 below.

Data processing and storage were commonly cited as demanding requirements. Moreover, different strategies were employed for integrating multi-sensor inputs. Most system developers are using or working towards manipulating their data in electronic format to facilitate real-time data fusion and analysis. It is not clear that real-time output is necessary for landmine use ban verification or humanitarian demining.

Not all the systems assessed operate from airborne platforms. Two of the systems - JAYCOR's stand-off landmine detection radar system and AlliedSignal/Kirtland Operations' MIRADOR - are ground-based, vehicle-mounted detection systems. Additionally, most of the EC JRC efforts identified focus on ground-level detection technologies. Because their sensors are mainly designed and oriented for vehicle-mounted use, these systems are not readily redeployable in an aerial search mode. The potential role of these systems would be limited, at most, to "ground-truthing" the results of wider-ranging aerial surveys for minefields.

DSWA also requested an assessment of the Proceedings of the EUREL International Conference on the Detection of Abandoned Land Mines, held 7-9 October 1996 in Edinburgh, Scotland, and select reports and findings presented at the Third International Airborne Remote Sensing Conference and Exhibition, held 7-10 July 1997 in Copenhagen, Denmark, for potentially relevant information. Various papers were reviewed that address WAD-oriented systems or technical approaches. Relevant technical information has been incorporated into this report. No system was cited in either conference's proceedings or reports as offering a functional WAD capability. However, various international RDT&E efforts by conference participants should be monitored for future progress.

## 7.3 SUMMARY OF FINDINGS ON OTHER DISCIPLINES.

No unique solutions were found in the survey of ten select disciplines not normally associated with landmine detection. Considerable overlap was found, though, in the WAD-applicable technologies used by the different disciplines, underscoring the limited number of truly promising approaches potentially available for wide-area landmine detection. Moreover, only a few novel approaches for WAD were hypothesized by technologists in the ten disciplines. In most of those cases, though, the technologies and systems suggested were already in use or under consideration or development for wide-area landmine detection, or were judged not feasible for wide-area detection applications.

The suitability of the different technological recommendations varied from discipline to discipline. Several of the fields investigated employ sensors whose resolution is inadequate (i.e., too coarse) for WAD. Others use or suggested the use of sensors that must be near to or in direct contact with the ground, an employment scenario judged infeasible for wide-area detection. Appropriately, technologists in the field of remote sensing offered the most viable technical recommendations for wide-area landmine detection, which in essence is a wide-area sensing task. However, their recommendations tended to reflect existing landmine detection techniques and do not appear to include any more promising approaches at present, particularly with respect to near-surface buried APL.

## 7.4 TECHNOLOGIES OFFERING NEAREST-TERM PROSPECTS.

While this study identified no individual sensor that alone provides a completely viable wide-area detection capability, three of the technologies investigated were seen to be more developmentally advanced, their application is better understood, or they are better suited overall for this type of task. Those technologies and some of their specific limitations, as noted earlier in this report, include:

- <u>Ultra-wideband, ground-penetrating, synthetic aperture radar</u> - Several organizations are examining this technology for APL detection, and technologists in several other fields noted the merits of ultra-wideband ground-penetrating radar employing a synthetic aperture for wide-area scanning. Trade-offs exist between resolution and penetration capabilities, which vary with the frequency ranges and bandwidths selected. Moreover, soil conditions affect penetration depth. Soil moisture, snow, and standing water greatly diminish penetration, while frozen ground and dry sand allow detections to great depths. Additionally, SAR imposes high data processing demands.

- <u>Infrared</u> - IR has been used extensively in many fields for a long time, providing a wealth of applications knowledge on which developers can draw. However, obscurants such as clouds, foliage, and rain can greatly impede sensor performance, and poor sensor resolution can limit target identification if an IR sensor is used alone.

- Hyperspectral imagery - This technology can be used to scan for stresses in the ground cover (vegetation) and for thermal signatures that may be associated with buried landmines. Performance is degraded or defeated, however, by vegetation, clouds, and other obscurants. While not identified and addressed in the Assessment 1 literature search, the potential value of hyperspectral imagery was discerned during Assessment 2 and Assessment 3 investigations.

All three technologies must contend with ground clutter and target discrimination concerns. It was also noted that certain sensors, such as IR, may be best deployed in an array configuration, and that an optimal platform might further involve a suite of interchangeable sensors or sensor arrays to meet a variety of environmental conditions.

These three sensor types appear to offer the greatest prospects for developing a wide-area detection system in the nearest term.[2] They received the most attention from researchers surveyed, and their use has been cited most often in various technical presentations and publications addressing wide-area landmine detection. Research and development efforts involving their use or integration into different systems bear continued monitoring. This observation is not meant to imply that other technologies may not offer better or even quicker solutions, only that available information highlights the strengths and current favor of the above three technologies among developers.

In addition to these technologies, the methodology by which technologies and data are combined, or "fused," merits particular attention. Such methodologies include raw data-level, feature-level, and decision-level data fusion, or synergizing the application of two or more technologies. Target recognition strategies that incorporate a "man-in-the-loop" would also need to be compared with automated systems. These concerns are discussed in greater detail in Section 4.

## 7.5 RECOMMENDATION ON TECHNICAL REQUIREMENTS SPECIFICATION.

It is apparent from this study and a variety of fora on technology developments, landmine detection programmatic discussions and presentations, and related conferences that there is a need for the establishment of uniform, validated, and widely accepted and understood technical requirements for the wide-area landmine detection mission. Such standards should address required levels of performance, operational parameters, and functional and physical constraints. These standards would provide a basis for developing and evaluating new detection systems. At present, there is no international standard for data presentation to facilitate exchange of information between international research activities; at a minimum, a standard set of mine signatures should be defined. This task falls under the rubric of the Joint UXO Coordination Office, cited in Section 7.6.

A set of "strawman" requirements was provided earlier in Section 1 of this report. This strawman should be refined to reflect the comprehensive needs of representatives of affected parties, including the arms control and compliance monitoring community, the humanitarian demining community (private industry and NGOs), technical developers, and technology policy makers. The Humanitarian Demining Information Center at James Madison University, or possibly the U.N. Department of Humanitarian Affairs - Mine Clearance Policy Unit, could serve as suitable fora for deliberation and development of these requirements. It is stressed that the user community must be involved from the beginning of these discussions. It is also recommended that the discussions be published at a well known site on the Internet, and that public debate and input be encouraged. Once a "requirement" is established, however, changes should be minimal and allowed only to accommodate validated operational needs or technological opportunities.

## 7.6 CHALLENGES FOR COORDINATING AND MONITORING DEVELOPMENT EFFORTS.

In the course of gathering and analyzing information for this study, some observations regarding strategic planning for, and coordination of, APL WAD-related RDT&E initiatives seemed evident. These embryonic and evolving initiatives may benefit from the application of an overarching, systematic approach for developing landmine detection systems, including the planning, coordination, or monitoring of the many technologists' efforts.

Research and development activities are strongly influenced by organizational focus, researcher aptitude or interest, ongoing or past research in an organization's other programs, component availability, or funding mandates. Moreover, systems tend to evolve through a variety of mechanisms, including iterative, follow-on efforts to improve earlier systems; efforts to screen promising technologies, such as DARPA pursued several years ago; or the application of improved data processing capabilities to older systems. These approaches, while drawing on the strengths of the researchers and organizations, may result in the potential redundancy of some RDT&E, the inefficient use of RDT&E resources, the bypass of other areas that may deserve attention, or lost opportunities for synergistic exploration of new approaches.

To ensure a broader and more comprehensive search for solutions, it is recommended that a coordinated, systematic methodology for investigating and assessing all potential technical approaches, sensor combinations, integration techniques, and deployment approaches be considered for development. This would require a "matrix approach" in which one guiding organization oversees RDT&E on sensor suites, data fusion methodologies and algorithms, and the overall coordination of efforts, including cooperative endeavors. Ultimately, a strategy could be formulated to progress beyond the RDT&E phase into production, deployment, and fielding. An announced life-cycle procurement plan would encourage wider cooperation and participation from a broad cast of potential organizations and personnel.

These observations, while derived from a totally different assessment methodology, underscore the conclusions of the September 1995 GAO Report on Unexploded Ordnance. The DoD's Report to Congress - Unexploded Ordnance Clearance, dated 25 March 1997, states changes have been implemented to rectify this situation across all of the functional areas involved in detecting and eliminating UXO. The organization to be employed is the Joint UXO Coordination Office, established on 1 October 1997 as the operational arm of the UXO Center of Excellence and collocated with the Night Vision Electronic Sensors Directorate at Fort Belvoir, VA.[3]

## SECTION 7

## ENDNOTES

[1] Per June 23, 1997 telephone conversation with Roger S. Vickers, Ph.D., Program Director, Geoscience and Engineering Center, SRI International, Menlo Park, CA.

[2] This finding was independently supported by Roger S. Vickers, Ph.D., Program Director, Geoscience and Engineering Center, SRI International, Menlo Park, CA, during June 23, 1997 telephone conversation.

[3] "Report to Congress - Unexploded Ordnance Clearance: A Coordinated Approach to Requirements and Technology Development," Office of the Under Secretary of Defense (Acquisition and Technology), 25 March 1997.

## APPENDIX

## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| A/D | analog-to-digital |
| APG | Aberdeen Proving Ground |
| APL | anti-personnel landmine |
| APL CP/B | Anti-Personnel Landmine Control Program/Ban |
| APOBS | Anti-Personnel Obstacle Breaching System |
| APS | active pixel sensor |
| ARL | Army Research Laboratory |
| ASD(SO/LIC) | Assistant Secretary of Defense (Special Operations/Low-Intensity Conflict) |
| ASTAMIDS | Airborne Standoff Minefield Detection System |
| ATDC | Army Training and Doctrine Command |
| ATL | anti-tank landmine |
| ATR | automatic target recognition |
| CASI | compact airborne spectrographic imager |
| CCD | charge-coupled device |
| CCVLS | Command Communications Video and Light System |
| CCW | Convention on Conventional Weapons |
| CECOM | Communications and Electronic Command |
| CINC | Commander-in-Chief |
| CLAMS | Cleared Lane Marking System |
| CV | Command Vehicle |
| DAP | distributed array processor |
| DC | direct current |
| DEA | Drug Enforcement Agency |
| DGPS | differential global positioning system |
| DIAL | differential absorption LIDAR |
| DoD | Department of Defense |
| DOE | Department of Energy |
| DRES | Defence Research Establishment Suffield |
| DSWA | Defense Special Weapons Agency |
| EC | European Commission |
| EDD | Explosive Demining Device |
| EMD | engineering and manufacturing development |
| EMI | electromagnetic induction |
| EMSL | European Microwave Signature Laboratory |
| EOD | Explosive Ordnance Disposal |
| FAR | false alarm rate |
| FFT | fast Fourier transform |
| FLIR | forward-looking infrared |
| FOLPEN | foliage-penetration |
| GAO | General Accounting Office |

| | |
|---|---|
| Ghz | gigahertz |
| GPR | ground penetrating radar |
| GPS | global positioning system |
| GSTAMIDS | Ground Standoff Mine Detector System |
| HDO | humanitarian demining operations |
| HEMMS | Hand-Emplaced Minefield Marking Set |
| HSTAMIDS | Hand-held Standoff Mine Detector System |
| IE | impact-echo |
| IGMMDT | Improved Ground Mobile Mine Detection Testbed |
| ILDP | integrated landmine detection program |
| ILDS | integrated landmine detection system |
| INS | inertial navigation system |
| IR | infrared |
| IRLS | infrared line scanning |
| JCM ACTD | Joint Countermine Advanced Concept technology Demonstration |
| JPL | Jet Propulsion Laboratory |
| JRC | Joint Research Centre |
| LANL | Los Alamos National Laboratory |
| LCC | linear correlation coefficient |
| LIDAR | light detection and ranging |
| LIF | light-induced fluorescence |
| LLNL | Lawrence Livermore National Laboratory |
| LWIR | long-wave infrared |
| MCB | Mine Clearing Blade |
| MEDDS | Mechem explosives and drug detection system |
| MHZ | megahertz |
| MICLIC | Mine Clearing Line Charge |
| MIR | micropower impulse radar |
| MIRADOR | minefield reconnaissance and detector system |
| MMD | minimum metal detector |
| MMW | millimeter wave |
| MRI | magnetic resonance imaging |
| MTBF | mean time between failures |
| MURI | multi-university research initiative |
| MVLS | Mobile Vehicle and Light System |
| MVP | Modular Vehicle Protection |
| NASA | National Aeronautics and Space Administration |
| NDE | non-destructive evaluation |
| NDI | non-destructive investigation |
| NDT | non-destructive testing |
| NIR | near-infrared |
| NIST | National Institute of Standards and Technology |
| NOAA | National Oceanic and Atmospheric Administration |
| NVESD | Night Vision and Electronic Sensors Directorate |
| OOTW | Operations Other Than War |
| ORD | Operational Requirements Document |
| OSMAPS | Opens Skies Mapping and Planning System |

| | |
|---|---|
| OUSD(A&T) | Office of the Under Secretary of Defense (Acquisition and Technology) |
| $P_d$ | probability of detection |
| PDRR | program definition and risk reduction |
| PM-MCD | Program Manager - Mines, Countermines, and Demolitions |
| PRF | pulse repetition frequency |
| RCS | radar cross-section |
| RDT&E | research, development, testing, and evaluation |
| RDV | Remote Detection Vehicle |
| RF | radio-frequency |
| RMS | resident mechanical spectroscopy |
| SAR | synthetic aperture radar |
| SASW | spectral analysis of surface waves |
| SIR | synthetic imaging radar |
| SLAR | side-looking airborne radar |
| SOCCENT | Special Operations Command Central |
| SOP | standard operating procedure |
| SPIE | International Society for Optical Engineering |
| SQUID | super-conducting quantum interference (or inductance) device |
| SSO | stability and sustainment operation |
| SU | spectral unmixing |
| TDI | time delay integration |
| TDSI | Time Domain Systems, Inc. |
| TEM | transverse electromagnetic |
| TIMS | thermal imaging multispectral sensor |
| TNA | thermal neutron activation or thermal neutron analysis |
| TODS | Tele-operated Ordnance Disposal System |
| UAV | unmanned aerial vehicle |
| UMR | University of Missouri at Rolla |
| UN | United Nations |
| USAF | US Air Force |
| UV | ultraviolet |
| UWB | ultra-wideband |
| UXO | unexploded ordnance |
| VMMD | Vehicle Mounted Mine Detector |
| WAD | wide-are detection |
| YPG | Yuma Proving Ground |