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Research of Ground-Penetrating Radar for Detection of Mines and Unexploded Ordnance: Current Status and Research Strategy

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PREFACE

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EXECUTIVE SUMMARY

A. BACKGROUND

This report documents the results of an Institute for Defense Analyses (IDA) assessment of the state of current research on ground-penetrating radar (GPR) as applied to countermine and unexploded ordnance (UXO) clearance. Despite significant long-term investment in GPR for mine and UXO detection, it remains true that no GPR system that meets operational requirements has yet been fielded; however, recent advances in several mine detection radars under development have produced significant improvements in detection performance and false-alarm mitigation over what was achievable only a few years ago. This report examines existing GPR research and development efforts with emphasis on missions where GPR has the potential to provide a unique capability and to achieve operationally meaningful performance. We identify data collections and analyses that will be necessary both to make decisions about the suitability of GPR for particular missions and to achieve performance gains necessary for operational utility.

As part of the GPR assessment effort, the Joint Unexploded Ordnance Coordinating Office (JUXOCO) sponsored a GPR workshop held at IDA in June 1999. Investigators from all currently funded GPR efforts in countermine and UXO were invited to present their work. An independent panel representing government, federally funded research and development center (FFRDC), and university expertise in GPR was assembled to assist the government in the assessment role.¹ Panel discussions were held during the course of the 3-day workshop and a 1-day follow-on meeting. This report is not an attempt to express a consensus of the panel, which likely does not exist; however, the comments and insights provided by panel members are reflected in the emphasis and conclusions of this report.

¹ Presentations to the workshop are summarized in Chapter 2 and panel membership is listed in Appendix B.

B. CONCLUSIONS

- Phenomenology controlling performance is not sufficiently well understood. Advanced development work must be preceded by concomitant research understanding.
- Too little analysis has been carried out on the data that has been obtained. A synergistic analysis effort that stretches across programs might provide real dividends.
- While there are exceptions, current system performance is typically limited by false alarms. That is, detection is clutter limited, not noise limited. Only when target and clutter characteristics are both well understood can signal processing be effectively applied.
- Much more effort has been spent studying target characteristics than has been spent on clutter. Efforts defining target signatures are necessary, and target-related research should continue; however, substantial efforts must be focused on clutter research and data collection.
- Predicting performance requires understanding sensitivities to the environment. Models will not provide the realistic data useful in algorithm development until the understanding of clutter is improved.
- Incorporation of diverse expertise in sensor hardware, algorithm development, modeling, and testing has been beneficial. The Multi-University Research Initiative (MURI) and the red team approach to the handheld standoff mine detection system (HSTAMIDS) program have resulted in better understanding of the sensor functionality and performance improvements.
- There is a need for controlled, repeatable testing to evaluate sensor performance independent of operator skill and technique, and not subject to uncontrollable alterations in the environment. This capability is important for comparing different sensors and tracking changes in performance with sensor modifications.

C. RECOMMENDATIONS

1. Research should be focused on forward-looking standoff detection, initially exploring detection of antitank mines in roads.
2. GPR counter-mine performance is limited by clutter, and clutter is not well understood.² Thus, the focus of research should be on defining, understanding, and measuring clutter. To that end, the following steps should be undertaken:

² Clutter is defined by returns identified by the sensor system as targets that do not correspond to intended targets or system noise, that is, real sensor responses to discrete items or environmental conditions not of interest.

- Determine the range of clutter and target data needed to support system design decisions, algorithm development, and modeling research.
 - Build a suite of research-quality data-collection instruments not constrained by operational requirements.
 - Collect and analyze clutter and target data, with a focus on clutter. Data collection should be driven by three concerns: better understanding clutter characteristics, providing training and test data for signal-processing algorithm development, and providing both input and validation data for EM model development.
 - Table ES-1 provides our recommendations for the system design and parameter space to be covered by the instruments and the data collection. These recommendations are for reasonable, notional parameters for the instruments and the experiments, but they do not represent the results of a rigorous study of the trade space or practical engineering considerations. As such, final designs should be based on an extensive red team effort involving hardware engineers, signal processors, modelers, and test designers.
 - Develop a research program to provide the necessary knowledge of clutter characteristics. Such a program should involve a careful physical and EM description of environments of interest, ranked in order of importance. These could be used to prioritize data collections. Clutter is highly variable, and that complicates its description. The focus of the research should be an attempt to group clutter into a limited number of classes relevant to system design. To that end, a careful evaluation of a combination of statistical and discrete approaches for clutter characterization is warranted.
 - Support research on the characterization of EM propagation and scattering in soils. Investigate a statistical paradigm similar to the atmospheric weak-scattering case. Bolster theoretical analysis with carefully calibrated measurements and computer modeling. Efforts should begin on simple, well-characterized media. As understanding is gained, more complex compositions should be tackled.
3. We should do a better job of exploiting data from current programs. There are two important facets of such an effort:
- Make data and specific analyses deliverable from contractors. Every effort should be made to ensure that data collections and analyses serve the broader goals of the countermine program.

Table ES-1. Data Collection Matrix

Parameter	Forward Looking	Down Looking
Frequency Range	200 MHz—4 GHz	200 MHz—6 GHz
Polarization	Full	Full
Grazing Angle	10–50 deg at 10-deg intervals	Full hemisphere
Aspect Angle	~0–180 deg at 10-deg intervals, as appropriate	Full hemisphere
Road/Terrain/Area	Unpaved dirt Macadam—various constructions Asphalt Flat terrain—bare and vegetated Hectare(s) for each	Increasingly complex media, small patches
Target type/configuration/quantity	Standard metal and dielectric targets AT mines Scatterable mines Submunitions Clutter 10's of each target type in each environment, surface and buried, as applicable	Individual target interrogation: buried mines UXO Discrete clutter objects Standard metal and dielectric targets
Spatial resolution	< minimum target size, best attainable with radar, centimeters	< minimum target size, best attainable with radar, centimeters
Waveform	Stepped frequency	Stepped frequency
Azimuthal Processing	SAR (cross-track)	3-D SAR
Antenna Height	3 m–6 m	Close coupled to earth
Standoff Range	3–20 m	0

- Set aside resources for independent analysis of data. Such efforts provide potentially valuable insights that are not likely to come out of program-driven analyses. An example is the Red Team analysis of HSTAMIDS³ data, which provided significant input to focus system improvements.
4. The HSTAMIDS red team is an example of how accessing a larger body of knowledge in the countermines area can pay dividends for a specific program. Research results coming out of the MURI and applied to data from the BoomSAR, Wichmann, and GeoCenters systems show significant performance improvements. Such interactions should be encouraged through a red team approach to system engineering decisions.

³ HSTAMIDS is the Handheld Standoff Mine Detection System under development for the U.S. Army. The system incorporates both GPR and electromagnetic induction sensors.

5. Measurement, modeling, and detection/discrimination algorithm development must be tightly integrated. As discrimination of mines from clutter is typically the problem faced by mine detection systems, discrimination algorithm development is the key to performance improvement. Algorithm success depends on the signals provided.
6. Sensors delivered to the government at the end of programs should be well documented and well calibrated.
7. Existing platforms from other DoD programs should be leveraged to the extent possible. Specifically, the Defense Advanced Research Projects Agency Ultra-High Frequency Ultra-Wide Band SAR (DARPA UHF UWB SAR) and the CECOM tactical unmanned aerial vehicle (TUAV) SAR should be tasked for data collection and baseline performance determination for countermines and UXO detection.
8. Develop protocols and equipment for standardized sensor testing.
9. Other specific recommendations are summarized in Table ES-2.

Table ES-2. Other Recommendations

Soil Characterization	<ul style="list-style-type: none"> • Develop a statistical description of soils, patterned on atmospheric physics • Develop numerical modeling approaches that accurately represent realistic soils • Initiate a measurement program to support above
Discrimination	<ul style="list-style-type: none"> • Continue modeling efforts to identify discriminants • Use above data collection for signal processing • Investigate utility of polarization • Investigate utility of spectral response • Curtail complex natural resonance research • Curtail 3rd harmonic research
Fusion	<ul style="list-style-type: none"> • Require analysis and reporting of target and clutter statistics for current data • Make raw and processed data deliverable. Initiate independent analysis • Task collection of coregistered data sets for <ul style="list-style-type: none"> • Forward-looking radar with NQR • Forward-looking and down-looking radar
UXO	<ul style="list-style-type: none"> • Establish a baseline for detection of high density of targets (impact areas) from an airborne platform • Study statistical requirements for airborne area delimitation • Study system engineering requirements for airborne radar

I. INTRODUCTION

A. BACKGROUND

The Institute for Defense Analyses (IDA) was tasked by the Joint Unexploded Ordnance Coordinating Office (JUXOCO) to review the status of ground-penetrating radar (GPR) research efforts in light of prospective missions in mine and UXO detection. This report examines existing GPR research and development efforts with emphasis on missions where GPR has the potential to provide a unique UXO- and mine-detection capability and to achieve operationally meaningful performance. We identify data collections and analyses that will be necessary both to make decisions about the suitability of GPR for particular missions and to achieve performance gains necessary for operational utility.

This report is not an attempt to survey all of the GPR research that has been conducted since the initial experiments were done 70 years ago. Significant past work that is not referenced explicitly has provided a basis of fundamental measurements and understanding. Here, we focus on the system development, data collection, modeling, and analysis conducted under current programs. Based upon this ongoing work, we make many suggestions for the direction of future efforts. Some of these suggestions may have been undertaken in some form in the past; however, it is our judgment that the data we identify as required to solve the most pressing current problems is not available in useful form. Often this is because past efforts were of limited scope or produced data that does not meet current needs. For example, modern signal processing will generally require coherent digital data for targets and clutter, and we know of no comprehensive library of such. If applicable data exists, no mechanism for cataloging and dissemination of past data to current researchers appears to be in place.

As part of the GPR assessment effort, JUXOCO sponsored a GPR workshop held at IDA in June 1999.⁴ Investigators from all currently funded GPR efforts in countermines and UXO were invited to present their work. The information presented to the workshop is summarized in Chapter II. An independent panel representing government, federally

⁴ Appendix B lists presentations to the workshop.

funded research and development center (FFRDC), and university expertise in GPR was assembled to assist the government in the assessment role.⁵ Panel discussions were held during the course of the 3-day workshop and a 1-day follow-on meeting. This report is not an attempt to express a consensus of the panel, which likely does not exist; however, the comments and insights provided by panel members are reflected in the emphasis and conclusions of this report.

A previous workshop examining new directions in GPR for mine detection was held in 1992 and chaired by Professor Glenn Smith of the Georgia Institute of Technology (Ref. 1). The report of that workshop recommended a number of areas for research. A great deal of work has been accomplished in the intervening years in system development, signal processing, and modeling. We will not attempt to cover all of the recommendations of the 1992 report individually, but note that a number of the conclusions remain true, and the recommendations remain applicable today. Particularly, we note the conclusions about the growing importance of models and signal processing, which have been borne out. We feel research in these areas should continue to grow. The requirement remains for the availability of realistic data covering a broad parameter space on targets and the environment to feed the modeling and signal-processing efforts. We identify specific data collection that would be most relevant to today's programs. Target discrimination continues to be the most pressing and obstinate problem. Finally, the need remains for controlled, reproducible testing of sensors.

In 1998, JUXOCO hosted a Radar Workshop for UXO Clearance (Ref. 2). Among the topics considered were future radar technology investments. The workshop did not produce any formal recommendations or conclusions. However, three investment proposals were highlighted in the report.

1. Develop a focused program that will sample target scattering phenomenology over the full range of frequencies that may be useful on a variety of known targets in a range of reproducible (not necessarily universal) conditions.
2. Develop standard environmental UXO test set(s) which replicate a variety of environmental scenarios and collect GPR data to establish environmental performance baselines.
3. Identify the fundamental limitations of the radar sensor.

All of these recommendations remain valid today, as do statements from the workshop notes citing the importance of a focused measurement program using instruments not

⁵ Appendix C lists panel members.

constrained by operational requirements and the need to understand real soils. In this report, we make many specific recommendations pursuant to these goals.

B. MISSION ROLES—WHAT IS THE NICHE FOR GPR?

The potential capabilities of GPR, if realized, make it an appealing tool for the detection of mines and UXO. Radar could detect both surface and buried metallic and nonmetallic targets not only in the roadway, but also through foliage such as tall grass or other ground cover, in all weather, and in the presence of smoke, mist, or other obscurants. Search could be performed rapidly from significant stand-off ranges. This promise, however, is yet to be realized.

Detection capability has been demonstrated for a number of radar implementations, particularly for close-in geometries and for metallic targets. In real-world tests, however, GPR consistently suffers from prohibitively high false-alarm rates (*FAR*),⁶ which indicates the general research investment strategy most likely to pay dividends. In identifying research requirements, we have considered the various proposed mission roles for GPR and attempted to identify those for which investment is likely to provide usable capability. Sensor design and performance requirements will differ for specific applications of GPR to various countermining and UXO mission areas: mine detection and UXO detection differ greatly in terms of the physical characteristics of the targets, environments, and depths at which targets will be found and to which detection must be accomplished.

In UXO detection, GPR has been proposed as a wide area search tool, as a detector of individual ordnance items at close range, as a precision localizer, and as an identification tool. Large tracts of land at base realignment and closure (BRAC) sites and formerly used defense sites (FUDS) must be separated into those areas that are clean and those that are likely to contain large densities of UXO, such as forgotten bombing targets, impact areas or disposal pits that may not be accurately reflected in the historical record. This mission would most efficiently be performed from an airborne platform, where high rates of search could be accomplished. Most traditional UXO sensors are ill-suited for deployment from an airborne platform, but a GPR synthetic aperture radar (SAR), if it could be made to work, is well suited to the mission. Because the mission objective is to

⁶ For example, the vehicle-mounted radars currently being tested have *FARs* of about 0.05 false alarms per m². In 1 km of unmined road 4-m wide, this sensor would report 200 false alarms. If the road were mined with 10 mines and the sensor detected all 10, there would be 10 real target returns buried among 200 false alarms.

detect dense populations of UXO, extremely high probability of detection (P_d) of individual UXO is not required. On the other hand, if clean areas are to be certified as clean, then high P_d will be required on individual items, and $FARs$ must be sufficiently low that clean areas can be distinguished as such.⁷

GPR has been proposed as a detector of individual UXO. In this mission, high P_d for individual UXO would be required to the depth specified for planned end use or the maximum penetration depth. $FARs$ must be low enough to avoid saturating excavation resources. GPR using, for example, imaging or complex natural resonance, has also been proposed as a discrimination tool. From a list of cues provided by another high P_d , high probability of false alarm (P_{fa}) sensor, truly hazardous, intact UXO would be identified. For this mission, the sensor needs high identification confidence with respect to the other alarms of the cueing sensor. Because all UXO contains metal and is amenable to detection using a magnetometer or metal detector, the key question for these missions is what additional capability can be had from GPR.

For demining, GPR has been proposed for all detection missions. Because many mines have little metal content, metal detectors are of limited use: increasing the sensitivity to allow detection of low metal mines results in overwhelming false alarms from metallic clutter. A sensor that responds to some feature of the mine other than metal is required, and GPR has been suggested as a way to meet this need. For countermine and humanitarian demining, GPR has been proposed as a standoff detector for surface and buried minefields and for munitions scattered by airborne platforms or by artillery. In this scenario, the Army has identified the ability to detect antitank (AT) mines alone as useful (Ref. 3); detection of antipersonnel (AP) mines as well would be even more useful.

Maximum standoff and maximum area coverage rate would be provided by airborne sensors. Few sensors currently under study are deployable from an airborne platform. GPR shows at least some promise in that regard. Others include infrared (IR), laser reflectance, and hyperspectral imaging (HSI). Previous implementations of IR and lasers on an airborne platform in the airborne standoff mine detection program

⁷ Attempting to apply a system with the vehicle radar performance to the airborne case leads to more extreme results. As a notional example, consider an impact area of 1 km² that contains 100,000 targets. A sensor with a modest P_d of 0.6 would report 60,000 real target returns in this km². If that same sensor had a false alarm rate of 0.05/m², however, it would report 50,000 false alarms for every km², whether it was contaminated or not. It would be difficult to pick out even an impact area in this background. If the FAR were many orders of magnitude lower, producing only hundreds of FA/km² (i.e., 10⁻⁴/m²), then it would be easy to identify the notional impact area. However, it would still be difficult to identify individual targets or certify areas as clean.

(ASTAMIDS) program have not shown useful performance in field tests (Ref. 4). Because of hardware difficulties and processing limitations, however, it is unlikely that the ASTAMIDS test results accurately reflect the physical limitations of laser and IR technology. Phenomenology studies are in early stages for HSI, making it difficult to predict capabilities.

More specific to the countermine mission is the need to detect, from a land-based, vehicle platform, surface and buried antitank mines, either individually or in groups, that have been planted on militarily useful routes. The Army has been funding R&D for down-looking systems that incorporate GPR into a sensor suite mounted at a standoff distance of a few feet from the front of a vehicle. There is, however, a great need to achieve tens of meters standoff distance in the forward-looking direction. As in the airborne case, GPR is among the few sensors currently under study that could play this role.

To be of any utility for the individual soldier on foot or for humanitarian demining, the radar sensor is required to detect targets that are far more stressing. The primary targets of interest are buried individual antipersonnel mines, which may be made almost entirely of plastic and are often only about 10 cm in diameter. Further, this mission requires detection in an off-road environment, where backgrounds are less homogeneous and present a more stressing clutter problem.

An important factor in focusing research resources is determining the appropriate niche for GPR in mine and UXO detection. Research efforts should be concentrated in areas where some meaningful capability is anticipated or where there are no other sensor options. It is clear that GPR is ill suited to some tasks, and there are other sensors available or under study that are likely to provide better performance once mature. On the other hand, for standoff detection—forward looking from a vehicle or side looking from an aircraft—GPR may be the best or only option available. For these missions, there are few competing sensor options, and none, including GPR, has yet shown robust performance.

C. BASELINE

GPR requires improvements in performance before it can be useful. Below we survey results of recent tests of GPR for various mission areas to quantify what performance improvements are necessary. Operational requirements documents (ORDs) are compared with what has been achieved to date for a variety of missions. Where possible, baseline performance is defined by the most recently published blind,

independently scored operational tests of the most recent technology. For some missions such a baseline does not exist.

Even where these results are available, they are influenced by the location and procedures of the particular test, as well as previously made engineering design choices in the systems tested. Thus, they are not easily extrapolated to general statements about capability. This points to important considerations about testing and evaluating detection systems that were noted in the report of the 1992 workshop. That is, there is a need to evaluate sensors in a standard environment on a common and reproducible target set where the influences of the operator are eliminated. This is particularly important for tracking system development and for evaluating competing sensor concepts. In field tests, true performance of sensors can be masked by contributions from footprint and coverage, as well as operator skill or fatigue, exploitation of visual cues, familiarity with the test site, or the means of presenting the data to the operator.

1. Mines

a. Hand Held (Down Looking)

The hand-held standoff mine detection system (HSTAMIDS) ORD sets the requirement for detection of surface and buried AP and AT mines at $P_d = 0.90$, with a *FAR* not to exceed 0.6 per m^2 (Ref. 5). Historically, handheld GPR sensors have been stressed by low-metal-content AP mines. See, for example, Reference 6, where systems incorporating GPR and EMI sensors were tested in 1996. Only about 69 percent of AP low-metal mines were detected, while more than 90 percent of AT low-metal mines were detected. The accompanying *FARs* were 0.5–0.67 per m^2 . Recent modifications in sensors under the HSTAMIDS program have resulted in performance improvements over what was achieved only a few years ago, but official results for the most recent tests are not yet available. Even so, at the ORD *FAR*, a soldier searching a 1-m wide lane will encounter a false alarm every 1.7 linear meters; thus, for any reasonable mine density, false alarms will far outnumber real detections.

b. Vehicle-Mounted Mine Detection (VMMD) (Down Looking)

The ground standoff mine detection system (GSTAMIDS) ORD (Ref. 7) describes the Army requirements for a ground-based vehicle platform detecting antitank mines on routes and roads. The P_d required (desired) is 0.90 (1.00) for surface laid mines and 0.80 (0.95) for buried mines, with a *FAR* not to exceed 0.01 (0.007) per m^2 . By way

of reference, a sensor meeting the ORD requirement searching a 4-m wide road would encounter a false alarm every 25 linear meters.

Tests of the VMMD program in 1998 at Aberdeen and Socorro set a baseline for performance of down-looking ground-based GPR vehicle systems (Ref. 8). The vehicles in this program were fitted with multiple sensor suites that included GPR, metal detectors, and IR cameras. The sensors were scored separately. For GPR only, on-road, the P_d s for surface AT mines (mix of metal and plastic) were generally 0.97 or higher, but the FAR was 0.03–0.08 per m^2 . For buried mines (also a mix of metal and plastic) on roads, the P_d s were slightly lower, mostly falling in the range 0.8–0.9, with a maximum of 0.98 and a minimum of 0.55, but the FAR was comparable. In the off-road tests, the FAR was much worse, ranging from 0.05 to 0.21 per m^2 .

c. Forward Looking

The Army currently has underway a 6.2 research program investigating forward-looking radar. It has not yet produced a performance baseline. Although one contractor has been pursuing a forward-looking system as part of an ongoing program, it is difficult to extract a baseline capability for forward-looking GPR from the available data. For example, available performance measures were calculated on a combination of GPR and IR data and on target sets that included a mixture of surface and buried mine targets.

d. Airborne SAR

The ASTAMIDS ORD sets the following requirements for minefield detection from an airborne platform: $P_d = 0.90$ for detection of surface minefields, 0.80 for detection of buried minefields, 0.80 for detection of scatterable mines, and 0.70 for detection of buried nuisance mines on roadways. The requirement for FAR is less than 0.5 minefield false alarms per km^2 (Ref. 3).

There have been no independent, scored tests for mine or minefield detection using a GPR from an airborne platform. SRI foliage penetration (FOLPEN) and Army Research Laboratory (ARL) BoomSAR (pseudo airborne) results show minefields in imagery. The results suggest a potential capability, but it is premature to extrapolate a general capability for standoff mine detection from SAR imagery.⁸

⁸ For detection of a mixture of surface and buried individual metal mines only, BoomSAR results from tests at Yuma Proving Ground give $P_d = 0.7$ for threshold detection with about 1,000 false alarms per km^2 (10^{-3} per m^2). With feature-based decision processing, the FAR is reduced by about two orders of magnitude. The more relevant capability is detection of minefields, rather than individual mines. The

2. UXO

a. Ground Based

Ground-based, stand-alone GPR sensors participated in Phases I and II of the Jefferson Proving Ground UXO technology demonstrations, where the objective was detection, localization, and identification of individual ordnance items (Ref. 10, 11). There were a number of mitigating factors, including stressing soil conditions and the target selection and emplacement, that may have prompted poor GPR performance. In addition, the hardware and data processing approaches tested here did not exhaustively probe possible parameter space, so it is unlikely that these results represent the physical limit of GPR performance for this mission. Nevertheless, for this test on a target set, which included bombs, artillery shells, and mortars, the GPRs tested did not detect individual ordnance items.

b. Airborne

Airborne platforms participated in Phases I and II of the testing of UXO detectors at Jefferson Proving Ground. The airborne sensors were also tested for detection of individual ordnance items, subject to the same test conditions as the ground-based systems. As above, it is unlikely that the systems tested represent the physical limits of attainable GPR performance. No target nomination from an airborne platform (including airborne GPR) could be attributed to a return from a specific, emplaced ordnance item. Whether this was due to detection or navigation failure could not be resolved from the data; however, results from close in (ground-based), stand-alone GPR platforms, where navigation was less of an issue, also indicate no detection capability for any GPR tested. In both cases false alarms were numerous. There is no independently scored, ground-truth baseline for detection of groups of ordnance items, from an airborne SAR.

BoomSAR data samples only one minefield containing M20 metal AT mines and a limited surrounding area. The minefield is identified as such by an ARL-developed minefield detection algorithm. The scanned sections outside the minefield area are not falsely identified as minefields (Ref. 9).

These results are, of course, from a research platform and were obtained on a limited data set. The analysis to determine the feature set was done on data from the same location as the scoring, although not the same subset of the data. Further, the results are for metal mines only.

D. CLUTTER

A review of baseline data quickly leads to the conclusion that in many cases, the fundamental problem of GPR performance is not the absence of a sufficient mine- or UXO-generated signal for the radar to detect.⁹ Rather, the problem is the multitude of signals originating from surface and buried clutter. Here, the concern is separating target signals from clutter signals. Thus, a thorough understanding of clutter becomes fundamental to understanding GPR performance and limitations.

We define clutter as returns identified by the sensor system as targets that do not correspond to intended targets or system noise, that is, real sensor responses to discrete items or environmental conditions that are not of interest. Clutter might be considered as a set of area- or volume-extensive attributes of the environment in which a GPR must work. Conversely, we might think of clutter as a collection of discrete, but undesired, targets to be separated from those we desire to detect. It is likely worthwhile to employ a mix of both views of clutter, and we do so here by defining two clutter study modalities: volume and discrete.

In either case, clutter statistics, which will quantify the ability of a feature or set of features to separate targets and clutter, must be measured for each potential discrimination feature of interest and will differ for each radar configuration. A library of target and clutter measurements taken in a variety of environments can be used to determine the robustness of clutter suppression approaches.

Features of discrete clutter objects (e.g., rocks, roots, cans, water-filled inclusions, etc.) may allow for discrimination and identification to reduce false alarms. It is possible but not currently known whether a significant fraction of false alarms arise from a small number of discrete types of clutter. This makes identification of the sources of false alarms an imperative part of any sensor improvement clutter study. If discrete objects or features of the ground can be identified and characterized, they can be screened out where they differ sufficiently from targets.

Studies of clutter are often neglected because of the desire to obtain data that is universally useful. Because the sensor must perform in a highly variable and continuously changing clutter environment, however, ways must be found to understand clutter. Framing experiments to study clutter is difficult because any study will be of the

⁹ An exception is likely to be detection of dielectric mines buried in soils with similar dielectric constants, where little or no contrast may exist.

specific clutter at a specific site as seen by a specific instrument. There will be great variability in the clutter itself, based on uncontrollable variables such as geology, climate, and history of use. Clutter at the same site may have temporal variations depending on recent weather patterns. Further, the clutter will depend on features of the radar itself such as grazing angle, spot size, resolution, frequency band, and polarization, as well as the processing. A clutter experiment therefore will require careful research planning, data collection, and analysis. Ongoing programs provide numerous data collection opportunities. There is a need to make sure the right data is taken, that it is analyzed, and that the analysis parameterizes the data in a meaningful way.

Recently, DARPA conducted a data-collection program that focused on understanding clutter for the buried mine and UXO problem (Ref. 12). Numerous sensors were tasked to survey four 1-hectare sites, with the goal of producing co-registered clutter maps from multiple sensor modalities for magnetometry, EMI, radar, and infrared sensors. Three radars participated in the study. All were sensors of opportunity, so in any event, the data collected explored dimensions determined by previous design choices. The experiment also experienced navigation difficulties that made interpretation of the data difficult. Nevertheless, algorithm work done by Paul Gader on GeoCenters radar data set resulted in a many-fold decrease in the density of false alarms at a comparable P_d (Ref. 13).

The necessary clutter study will require an effort such as this. This experiment should be conducted in a variety of clutter environments on well-characterized sites. Research-grade sensors with the flexibility to explore the widest accessible parameter space are required. Only through an effort such as this can we build the library of clutter data necessary for making engineering design choices, supporting modeling of real-world conditions, signal processing, and algorithm development, and for determining the robustness of sensor performance.

E. GPR SYSTEM CONSIDERATIONS

GPR design is complex and challenging because of the array of hardware and system choices and the coupling of many of those choices. The intent of this section is to provide a brief discussion of some of the choices that can be made and their implications.

The most fundamental choice in GPR is the center frequency and the bandwidth of the radar. Low frequencies provide improved soil penetration; the depth at which targets must be detected and the soil types within which they must be detected drive the choice for the lowest frequencies to be transmitted. For example, UXO detection would

generally call for lower frequencies than mine detection because of the greater depths at which targets may be located. Practical limits on low-frequency performance are often determined by the maximum size of the antenna that can be deployed. Range resolution is governed by bandwidth, with the achievable resolution given as the speed of light in the medium divided by twice the bandwidth

$$\Delta R = \frac{c}{2B\sqrt{\mu_r\epsilon_r}} \quad .$$

where c is the speed of light, B is the bandwidth, μ_r is the relative permeability, and ϵ_r is the relative dielectric constant. Thus, if high resolution in range is desired, wide bandwidth is required, and the higher the center frequency, the narrower the percentage bandwidth for a given resolution and the more straightforward the radar design job. Because of the dispersive properties of soil, high frequencies will be attenuated more than low frequencies. Rather than considering the waveform that is transmitted, the GPR designer must plan his processing and detection strategies around the expected spectrum of the return after propagation to the target, reflection, and propagation back to the radar antenna. Thus, having low frequencies that penetrate well may be of little consequence if the detection algorithm depends on fine resolution and the higher frequencies that provide bandwidth are severely attenuated. The chosen frequency regime also controls less obvious radar characteristics such as achievable cross-range resolution in SAR systems and the level of RFI with which the system must contend.

Most GPRs for mine detection are wideband devices because good range resolution is required to separate targets from clutter. Two general approaches to obtaining wideband performance are available to the system designer. Each has advantages and disadvantages. The first utilizes waveforms having time-bandwidth product that is near unity. These systems are represented by the family of impulse radars that have been developed for ground-penetration missions. The major advantages of an impulse radar are that lower dynamic range receivers are required to discriminate against clutter, the waveform generation time is short, and a high-range resolution display is available with little or no processing. The major disadvantages are the need to control RF dispersion over a wide instantaneous bandwidth, susceptibility to radio-frequency interference (RFI) because of the wideband receiver front end, the need for very high speed analog-to-digital converters (or the inefficiency of a sampling oscilloscope approach) for waveform capture, and difficulty in controlling the transmitted spectrum. Impulse radars also tend to be limited in average power because breakdown effects limit peak power and duty factors tend to be low. Our observation is that many GPR designs are now moving away from

impulse implementations because of the disadvantages, particularly the difficulty in choosing and implementing an optimum spectrum for a given application.

The alternative to impulse is to employ a waveform with a time-bandwidth product much greater than one. Such systems have been implemented using stepped frequency, linear FM chirp, or phase codes. The major advantage of stepped frequency or LFM chirp is that the frequency spectrum can easily be chosen to fit what the designer considers optimum. In fact, notches can even be placed in the transmitted spectrum to avoid interference with or by other systems. Stepped-frequency waveforms, in particular, allow narrow instantaneous receiver bandwidth, lower bandwidth analog-to-digital converters, and wider dynamic ranges. This last advantage is often offset by a need for the wider dynamic range because the large surface clutter return and target returns are not temporally separated, as in an impulse system. Other advantages of high time-bandwidth product waveforms are higher average powers, an ability to tailor the frequency response on receive through processing, and the coherent waveform generation required for image processing. Phase and amplitude calibration and equalization are easily accomplished at each discrete frequency step. The major disadvantages are the required dynamic range mentioned above and the time required to generate one complete waveform.

A waveform and bandwidth having been chosen, the GPR designer must implement an antenna commensurate with the bandwidth. Antenna design becomes particularly critical in systems whose geometry provides little standoff from the surface of Earth. A major problem with wideband antennas is eliminating internal reflections over their entire frequency band. Such internal reflections result in antenna "ringing" that can hide target returns in systems that operate close to the surface. In down-looking systems, that problem is exacerbated by the very large surface clutter return that may also reverberate within a poorly matched antenna structure. Closely coupled antennas can reduce that problem, as can the use of cross-polarized antennas that tend to discriminate against the surface clutter return. While no designer would intentionally choose an antenna known to produce significant internal reflections, two design approaches are generally viable. In one, the designer makes heroic attempts to reduce antenna internal reflections, thereby simplifying the signal-processing problem. Such an approach is illustrated by the Wichmann radar, where the array antenna is designed to effectively eliminate internal reflections. The second option is to live with a certain amount of antenna internal reflections and take those out in signal processing. This is most easily done with a stepped-frequency system, where the internal reflections can be measured at each frequency and then coherently subtracted from the return. The flaw in such an approach is that the

reflections will depend to some extent on the details of the surface clutter return, and as that changes, coherent subtraction may be less effective. Internal reflections are of less concern in standoff radars, but at the low frequencies often employed in GPR, they may be a problem even in that case. In particular, at low frequencies the entire structure on which the antenna is mounted becomes part of the radiating structure, and reverberations may linger in time. That problem has been noted in several GPR implementations.

Signal-processing and display options are strongly driven by the waveform choice and the antenna implementation. For example, with a single antenna that is manually scanned, it is very difficult to generate a display output more sophisticated than a simple one-dimensional range profile. Such a display is available with little or no processing from an impulse system and with simple pulse-compression processing from a large time-bandwidth product system. Linear array antennas or antennas that scan across the mine lane provide more flexibility in display. A linear array can be used to provide a waterfall plot of time (range) images closely spaced in the cross-track direction, as in the Wichmann radar; a real aperture two-dimensional image, as in the GeoCenters display; or a form of synthetic aperture image. A scanned antenna can also be used to produce a synthetic aperture image. Finally, scanning in both cross-track and down-track allows formulation of three-dimensional images. Doing so, however, requires careful attention to knowledge of antenna position and correction of propagation effects within the soil.

F. ORGANIZATION OF REPORT

We seek a clear connection between an operational concept for GPR in counter-mine and UXO clearance operations and a focused plan for conducting the necessary supporting research and obtaining needed engineering design data. The focus of the report is on defining the research necessary to design an optimal operational system, not to design the operational system forthwith. As such, it is important to remember that the recommendations herein are for instrumentation and experiments to collect necessary data, rather than to support operational requirements. We will generally want data-collection experiments to cover a wider range of operating parameters than would be practical for a fielded system, so that we can be confident that the limits of the operating system are optimally chosen.

Operational concepts based on standoff detection that is vehicle-mounted forward looking or airborne side looking will have different research requirements than those based on a close-in down-looking sensor. Primarily, the difference in illumination geometry guides research emphasis. In the down-looking case, the close coupling of the

antenna to the ground produces effects that are not of concern for standoff applications. The competing clutter for the two geometries will differ. For forward-looking radars, where most of the energy forward scatters from the surface, there will be no need to remove a dominant ground-bounce from the radar data; however, an inability to gate out surface clutter will require unique clutter suppression efforts. Defining the benefits derived in a forward-looking system, which provides the opportunity to obtain returns from multiple grazing angles for both targets and clutter, will require its own research effort. In addition, differences in mission and potential targets will dictate other research requirements. Chapters III and IV discuss the research requirements for standoff and close-in GPR, as well as unique information that can be had from experiments in either geometry.

In Chapter II, we preface this with a short summary of the presentations to the workshop. There are numerous research efforts that must be undertaken to advance GPR in either application. These are discussed in Chapters V (soil characterization), VI (discrimination), and VII (modeling). Since it is likely that radar will be paired with another sensor for any application, Chapter VIII discusses data needs for sensor fusion studies. Chapter IX discusses special considerations for UXO detection. Chapter X summarizes major conclusions and recommendations arising from this effort.

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II. WORKSHOP PRESENTATIONS AND RADAR DESCRIPTIONS

A. SUMMARY OF WORKSHOP PRESENTATIONS

Here we summarize the material presented by researchers in the JUXOCO GPR workshop in June 1999. In all, 17 papers were presented over the 3-day workshop.

1. Handheld and Vehicle-Mounted Mine Detection Systems, *Marconi*

Dave Lang described the Marconi hand-held mine detection sensor incorporating a GPR. It was developed under funding from various Night Vision Electronic Sensors Directorate (NVESD) programs, most recently HSTAMIDS, and previously under funding from the Defense Advanced Research Projects Agency (DARPA). The sensor is intended to detect buried AP and AT mines in both on- and off-road environments. The current implementation uses a stepped-frequency waveform in the frequency bands from 0.5 to 3 GHz with a zigalog antenna and from 4 to 6 GHz with a horn antenna. Target nomination is by threshold exceedence.

The Marconi VMMD system is a down-looking, vehicle-mounted array based on the handheld system design. Its development was supported by NVESD, and it is currently supported in the Mine Hunter/Killer program. The evolution of the system from the 1-m array prototype in the VMMD program to the 1998 ruggedized version was described. The system uses a stepped-frequency waveform in the 0.5- to 2.1-GHz frequency band. In tests in prepared mine lanes at Aberdeen and Socorro, the system detected 70–100 percent of buried low-metal mines with *FARs* in the range of 0.02–0.06 per m². Algorithm improvements made during these tests resulted in both decreases in *FAR* and increases in P_d .

2. Vehicle and Unit Area Radars, *GeoCenters*

Rob Siegel described the vehicle-mounted focused array radar that GeoCenters developed under the VMMD program and a unit area clearance concept being developed for humanitarian demining. The VMMD system includes a 3-m wide vehicle-mounted radar, which is coupled with EMI and IR sensors. The radar covers 0.7–1.3 GHz, is

polarized with the E-field in the cross-track direction, and is implemented in an array of 15 transmit and 15 receive transverse electromagnetic rhombus (TEMR) horn antennas. Focusing in the cross-track direction is accomplished by appropriately time gating a subset of the transmitters and receivers for each voxel location. The antenna pattern determines down-track resolution. Initially, the standard processing and target selection was done using a statistic obtained by summing the energy of all voxels from the surface down. This resulted in high P_d , but many false alarms. In later implementations [the advanced technology demonstration (ATD) automatic target recognition (ATR)], three-dimensional processing was added and false alarms were reduced by an order of magnitude ($P_d = 0.83$, $FAR = 0.038/m^2$, as reported by P. Gader).

For the humanitarian demining concept, GeoCenters is working to extend the application of its radar to AP mines. Efforts are directed at improving the focus, increasing the density of voxels, increasing the bandwidth, redesigning the antenna, and modifying the processing algorithms.

The GeoCenters work was sponsored by the U.S. Army VMMD and humanitarian demining programs and supported with internal GeoCenters funds.

3. GPR Developments at SRI, International

Joel Kositsky described several aspects of the sponsored SRI program. These included forward-looking, ground-based GPR; airborne GPR; and prospects for harmonic radar detection of mines and UXO.

Although the early SRI work on FOLPEN radar and GPR was accomplished using an impulse waveform, the current ground-based system utilizes a stepped-frequency waveform in the 300- to 3,000-MHz band. The system is fully polarimetric and accomplishes cross-track resolution by synthetic aperture processing of signals obtained over a 4-m cross-track aperture. The goal is to be clutter limited at all frequencies, although there is evidence that RFI may be a limiting factor at some spot frequencies. In the forward scan mode, the system collects data from a region stretching 7 to 60 m in front of the host vehicle. This system is not intended as a prototype of a fieldable GPR, but rather as a data collection asset. Its forward speed of advance is very slow, being limited by the need to stop and stabilize the vehicle before initiating each SAR scan. In its current version, the radar is affected by self-clutter due to ringdown in the antenna and vehicle structure. This can be mitigated somewhat by coherent subtraction, although residues remain. Tests on buried targets show that detectable signatures can be located at known target positions. Additional work is under way to improve false-alarm rejection.

Once the ringdown problems are solved, this system should be a valuable asset for collecting data on a variety of targets and clutter contexts.

SRI has conducted many airborne GPR experiments over several years. The airborne system has generally been an impulse transmitter with heterodyne receivers. Modest soil penetration has been achieved, and very large targets can generally be discerned. SRI has proposed using airborne GPR as a wide-area search and assessment tool.

Harmonic radar attempts to detect man-made objects by third harmonic re-radiation. It depends on the existence of a metal-insulator-metal junction in the targets being sought. This can occur when two pieces of metal are in poor electrical contact, particularly in moist environments. The advantage of harmonic radar is the lack of response from natural objects, which virtually eliminates clutter as an interference source. Unfortunately, the signals exhibit a range dependence of $1/R^8$, which makes this a very short-range search system. The most serious drawback of harmonic detection is the uncertain nature of the signal. SRI reports that individual UXO signals occur in only a fraction of items tested and that they are not reliably reproduced from day to day. A UXO field may have several inadvertent junctions leading to harmonics, or it may not. Thus, while harmonics may serve to detect targets with some probability, the lack of signal does not reliably indicate the lack of targets.

4. Three-Dimensional GPR (Circle SAR), *Mirage*

Phil Fialer's presentation outlined work underway at Mirage Systems to develop a "Circle SAR."

Although most synthetic apertures used in SAR are linear, the term "circle SAR" refers to collecting coherent data over a circular synthetic aperture. A circular aperture, in conjunction with a wide-band waveform, allows the formation of three-dimensional radar resolution cells ("voxels"), which can, in principle, allow separation of buried targets from surface clutter. This technology was originally developed under Department of Energy (DOE) support to search for deeply buried hazardous waste containers; the extension to smaller, shallower targets is a recent effort funded by DARPA. The radar uses a frequency-modulated continuous wave (FMCW) waveform covering 20 to 1,200 MHz. This frequency band was originally chosen to support the deep target detection mission and is probably not optimum for shallow buried mines. The useful band is limited to 100–1,000 MHz by the log periodic antenna now used. The ultimate goal has been to mount the system on a helicopter or light aircraft, but to date testing has involved

a wheeled trailer with an extended mast. To achieve the best three-dimensional resolution, relatively steep grazing angles in the region of 15–75 deg are desired, with best results near 45 deg.

Besides using the novel circular SAR aperture, Mirage employs a novel system of ground-emplaced repeaters to provide the precise radar location data needed for SAR processing.

To date, the ground-based system has been used to obtain good quality three-dimensional signatures of metal mines buried in a homogeneous sand environment.

5. Electromagnetic Wave Detection and Imaging Transceiver (EDIT) for Shallow and Deeply Buried Objects: Plastic and Metal Landmines, Tunnels and Buried Structures, and Unexploded Ordnance, *Stolar Horizons*

Presented by Larry Stolarczyk of Stolar Horizons, the briefing described a variety of work for underground imaging and communications. For humanitarian demining, a resonant microstrip patch antenna (RMPA), incorporating acoustic navigation, has been constructed in a handheld package. In initial testing at Fort A.P. Hill targets including VS1.6, M15, and Val-69 mines were observed reliably, but no *FARs* were reported. Imaging of UXO by bistatic probes for transmit and receive on either side of UXO was proposed. This work was sponsored by U.S. Army Humanitarian Demining, Air Force Materiel Command, and Army Research Office (ARO). Other applications discussed included (1) underground radio communications, (2) underground imaging for mining applications, and (3) tunnel detection with a REMGA (resonant EM wave gradiometer antenna) system.

6. High-Resolution GPR, *Planning Systems*

Tom Witten from NVESD described the Planning Systems down-looking, multi-channel, stepped-frequency GPR for mine detection. An array of six transmit and seven receive log spiral antennas are mounted on a cart in a staggered configuration in two rows. The stepped-frequency system covers 0.8 to 2.0 GHz. Opposite circular polarization is used for transmit and receive. The array width is 33 in., and 12 cross-track samples are taken, 1 for each transmit antenna with its 2 neighboring receive antennas, for a spacing of 2.76 in. SAR processing is used for image formation in the cross-track direction. The radar operates 6 to 8 in. above ground. This work is sponsored by NVESD.

7. Forward-Looking Radar for VMMD, Jaycor

Jaycor gave a presentation of results obtained with the forward-looking radar developed for the VMMD. Unlike other vehicle-mounted GPR systems, this radar is designed to look ahead over a search zone 5–30 m in advance of the vehicle. The goal of this effort is to maintain a convoy speed of at least 16 km/hr. The system uses a single wide-beam transmit antenna and a combination of two receive antennas that yield an estimate of the cross-track position of the detected object by means of pseudo-monopulse type of processing. The nominal band is 500–4,000 MHz, although preliminary results have been limited to 1,000–4,000 MHz. The hope is that the lower frequencies will better penetrate the soil, while the higher frequencies excite resonances in land mines. The actual degree of ground penetration for this system is probably not great, given the low grazing angles, microwave frequency band, and probable soil losses. Nonetheless, even without much penetration capability, it may be possible to detect buried mines through their surface disturbance signatures; the detection of surface mines is also a mission for this system.

Using this system in prepared mine testing lanes, a relatively high probability of mine detection in the range of 85–100 percent has been achieved. The corresponding *FARs*, however, are also high, in the range of 0.08–0.2 alarms/m². The Army requirement quoted by Jaycor on *FAR* is 0.05/m², which does not appear to be unduly stringent given that it corresponds to 1 alarm/20 m² or 1 alarm for every 5 m of advance on a 4-m wide roadway.

The GPR is only a part of the engineering effort that has gone into this system, which integrates radar, global positioning system (GPS), and forward-looking IR with signal processing and sensor registration functions.

One issue with this system is how well the transverse location processing will work in areas of high alarm density, where multiple objects may contribute to return in a given range cell.

8. Land-Mine Detection Using Micropower Impulse Radar Imaging, LLNL

This work was carried out under the Lawrence Livermore National Laboratory (LLNL) Micropower Impulse Radar Project, with collaboration among LLNL, the University of California–Davis, and Purdue University. Stephen Azevado of LLNL made the presentation.

Micropower impulse radar (MIR) technology is an outgrowth of laser fusion diagnostic work at LLNL. Current MIR sources provide impulse waveforms with the majority of their energy in the 1- to 4-GHz band. In addition to humanitarian demining applications funded by the Defense Special Weapons Agency (DSWA) and the Army, MIR is being used to track the rotor blades on the V-22 tiltrotor aircraft (Navy), for medical diagnostics (Army), and for bridge inspection [Department of Transportation-Federal Highway Administration (DOT-FHWA)]. The focus of this presentation was on humanitarian demining, with emphasis on the use of imaging (particularly three-dimensional imaging) to reduce clutter and aid detection.

Through finite difference time domain (FDTD) simulations and measurements, LLNL is exploring ground-coupled and offset image formation in monostatic and bistatic geometries. Ground coupling provides better results, but at the expense of mobility. A major problem in image formation using back propagation (the preferred method for MIR) is accounting for the effects of soil permittivity on propagation. A minimum phase-error variance technique developed by LLNL is used to provide a permittivity estimate, allowing optimum image formation.

In humanitarian demining, computational requirements and system cost are important factors in utility. For its three-dimensional imaging system, LLNL estimates that real-time imaging will require 20–40 Gflops of processing and that using current parallel-processing techniques, a system could be built for about \$50K. A lab prototype man-portable detector has been constructed and tested. The system is based on the needs of humanitarian deminers working in areas cleared of brush or foliage. The antenna array employs ground contact antennas and images a 1 m² area. Eighteen tests of the prototype system were conducted through April 1998 in lanes containing three soil types. Six to eight mines were emplaced in each lane, along with 30–50 introduced clutter objects. LLNL compared MIR performance to AN/PSS-12 performance, where the PSS-12 was claimed to have given a detection rate of 44 percent with 31.8 false alarms per detected mine, compared to a detection rate of 85 percent for the MIR with 14.6 false alarms per detected mine. Note that while the MIR showed much better detection performance, the total number of false alarms provided by the two systems was similar.

9. OSU's GPR Application on the Detection/Classification of UXO and Anti-Personnel Mines, *Ohio State University*

This work was carried out at the Ohio State University ElectroScience Laboratory (OSU/ESL). Various parts of the work were done in collaboration with other organiza-

tions. Chi-Chih Chen of OSU/ESL gave the presentation, which was divided into sections covering UXO detection and classification, landmine detection and classification, and general capabilities.

UXO work from 1994 to the present was described first. In these efforts, OSU/ESL teamed with the Battelle Memorial Institute and the Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL). The Army Environmental Center, the Naval Ordnance Disposal Technology Division, and the DoD Environmental Security Technology Certification Program provided support. A robotic tractor carrying an induction coil sensor, magnetometer array, and impulse GPR system with a cross-polarized antenna was developed and deployed. The GPR used cross-polarized transmit and receive antennas to reduce direct antenna coupling and surface clutter. More recently, a dual polarization, stepped frequency system that covers 1- to 400-MHz has been constructed. That system is being used to explore UXO length estimation using complex natural resonance signatures. Results provided based on testing with some typical UXO targets indicated excellent agreement between estimated and actual length in most cases. The exception noted was the BDU-33, whose estimated length was about 40 percent longer than its actual length.

The second part of the presentation covered landmine GPR systems, an effort also performed in a teaming arrangement with Battelle, but supported by the Office of Special Technology at Indian Head, Maryland, and the ARO Multi-University Research Initiative (MURI). For this effort, a focused reflector, pulsed or CW GPR that covered the 1–6 GHz frequency range was developed. System design allowed a 4-foot standoff. In addition, a near-field probe antenna was also developed and deployed with the system. The GPR system was used in mine detection tests in concert with an EMI and an IR system, and results of various fusion algorithms were discussed.

The final section of the presentation discussed signal-processing domains with potential utility for mine and UXO detection and classification. These included complex natural resonance phenomena explored in the time and frequency domains, polarization processing using the complete complex polarization scattering matrix, and spatial/time template correlation. Simulated data were used to provide examples.

10. Radar Detection of Nonmetallic Simulant Land Mines, *CRREL*

This work was carried out at the U.S. Army Corps of Engineers CRREL, funded in part by the Project Manager—Mines, Countermine, and Demolitions. Gary Koh gave the presentation.

The approach for this research was to obtain radar signatures of plastic simulant mines buried in a well-characterized test site using both a conventional FMCW GPR and a prototype radar array imaging system. Multiple polarization data was collected. The effects of bandwidth and orientation on simulant signatures were provided in the presentation, along with a comparison of AP mine simulant and rock signatures. In outdoor measurements taken at CRREL, the effects of frozen ground and snowmelt on the detection of buried mines were explored. Images were provided of both cases. Finally, the effects of array processing on image formation were discussed, and simulated results of tomographic imaging of a plastic mine buried in frozen ground were provided. Operating characteristics for a Phase II microwave camera were shown. A CW stepped-frequency system covering 1.6–3.2 GHz and providing full polarization scattering matrix data is planned. It will feed a 1.1-m long antenna array consisting of 20 transmit and 20 receive probes.

11. Ultra-Wideband Radar Technology Development at ARL UXO/Mine Detection, *Army Research Laboratory*

Jeff Sichina of ARL presented the work. The first part of this briefing was a general introduction to the use of SAR in mine detection research, with special emphasis on the facilities and capabilities of ARL. Basic system design issues were discussed, as well as the technology developed at ARL to overcome environmental interference in impulse radar systems. Although most of ARL's experience and technology development has been directed to impulse radar systems, they offered an objective discussion of the relative advantages of impulse and chirp waveforms. They are clearly considering developing a chirp-based system at ARL.

In addition to the typical side-looking SAR geometry, ARL has investigated alternative methods of forming synthetic apertures. These include forming a circular aperture roughly centered on the area to be imaged and a forward-looking SAR in which the aperture is formed by moving the antenna phase center laterally perpendicular to the track of a vehicle. In the latter, the system can be used to collect data relevant to the development of a real-aperture, forward-looking radar before making a major commitment to a specific antenna design.

The work being done in collaboration with Duke was described from an ARL perspective. The goal is to develop a detailed signature library for improved automatic target recognition. ARL intends to exploit these modeling techniques to include the effect of random rough surfaces.

The workers strongly suggest that despite the resources invested in GPR over many years, achieving adequate detection performance may require the fusion of radar with other sensors. Exploring this will require careful planning of coincident data collection programs.

12. Modeling Synthetic Aperture Radar Signatures of Buried Mines and UXO, *Duke University*

This work was a collaboration among researchers at Duke University and the ARL. The presentation was given by Larry Carin of Duke.

As speed improvements in both processors and algorithms have permitted more detailed problems to be addressed and more variations to be considered, method of moments (MoM) and related means of solving electric field integral equations to determine the scattering from mines and UXO have received greater emphasis. This briefing discussed applications of integral equation solutions to predicting mine signatures with enough fidelity to support automatic target recognition. The results indicated good correspondence between measured and calculated signatures of metallic and dielectric mines in homogeneous lossy soil media and showed the sensitivity of the computed signatures to small variations in mine attitude. Polarimetric calculations showed that V-pol signatures were generally dramatically greater than H-pol for small dielectric mines in lossy soils. Results also showed characteristic spectral shapes due to interference between scattering centers for large metal mines such as the M-20. This effect is particularly significant because most large discretized targets that could otherwise give false target indications seem to lack these characteristic spectral envelopes.

This presentation also demonstrated the use of the fast-multipole method (FMM) as an alternative to MoM in solving the electric field integral equations (EFIE). The advantages are significantly reduced memory requirements for large problems, as well as fewer computational steps.

These techniques permit problems to be addressed in enough detail for the results to be useful, without placing unacceptable burdens on computer processing. A key issue not covered is the practical applicability of these solutions to realistically random media.

13. Subsurface Detection Research at *Georgia Tech*

This presentation was a joint paper by Waymond Scott and Glenn Smith that covered several topics. First, they explained how the sophistication of EM modeling has reached a level which allows it to replace the traditional empirical process of developing

GPR for landmine detection. As an example, they showed a comparison between a finite difference time domain analysis and measurements of a separated aperture bistatic antenna system. Similar comparisons between theory and measurement were shown for a V-dipole antenna structure.

Second, they discussed measurements made at Georgia Tech on several antennas in use by different contractors in the Army's HSTAMIDS program. By isolating the antenna subsystems from the GPRs and subjecting them to consistent tests in a controlled environment, it was possible to determine the specific role of the alternative antenna designs on the performance of the full detection system. From these experiments it was concluded that small plastic antipersonnel mines could be detected using both antenna options, provided the environment was clean. It could thus be concluded that the antennas were not the limiting factor in mine-detection performance.

Third, they described the possibility of designing a system to exploit near-surface evanescent waves for shallow mine detection. The final topic was a description of experiments in which RF radiation was used in concert with mechanical excitation to detect acoustic resonances within the mine structure. These resonances are characteristic of the mine and should be good discriminants against clutter. Because the radar is used solely to detect surface vibrations using Doppler, the issues of soil loss and radar clutter do not arise. Measurements to date have shown the feasibility of using this phenomenon for mine detection, albeit in highly favorable environments.

14. A Two-Dimensional Hand-Held Microwave Imager for Antipersonnel Mines, *University of Texas, Arlington*

The University of Texas at Arlington carried out this work with funds from the Army Research Office. Jonathan Bredow made the presentation.

The focus of the reported work is on a conceptual hand-held antipersonnel mine detector with a search head employing a circular array of transmit-and-receive antenna pairs. Efforts to date have concentrated on FDTD simulations to guide selection of antenna characteristics and laboratory studies to assess parameters such as the number of antenna positions required, calibration, clutter removal, and the effects of different target types. The conceptual instrument would operate in two modes, a standard imaging mode and a superresolution imaging mode. Both modes employ linear polarization, transmission of multiple simultaneous frequencies, and multiple angle backscatter geometries. In addition, the standard imaging mode transmits stepped frequencies over the 2–4 GHz and 4–8 GHz bands, while the superresolution mode uses frequencies of 3 and 6 GHz.

The laboratory setup for imaging consists of a rotating soil tank to provide a simulation of a circular antenna array and single bistatic illuminating and receiving antennas. Data have been collected for quasi-monostatic geometries at 60-deg incidence (30-deg grazing) and with normal illumination and receivers at 17-, 35-, 45-, and 60-deg incidence. Data have been collected over a 2- to 10-GHz frequency range in dry sandy loam and dry sand. Targets have consisted of circular and square metal lids and cans, circular and square Styrofoam blocks, and RTV rubber/ABS plastic landmine simulants. FDTD modeling has supported the measurements. The presentation provides output for a number of cases of measured and simulated images, with a focus on differences caused by shape and materials. Block diagrams are provided of the postulated instrument, and comments on its application are included.

15. ATR Algorithm Performance for the BRTRC-Wichmann Ground-Penetrating Radar System, *Duke University*

This work was carried out at Duke University under the ARO MURI, utilizing data provided by the BRTRC-Wichmann GPR. Leslie Collins of Duke gave the presentation.

The goal of the effort was to develop and demonstrate automatic detection and identification algorithms for signals obtained by the BRTRC-Wichmann GPR. The algorithm development was data driven, utilizing data recorded from 21 mines and 11 clutter sources in the JUXOCO calibration and test grids at Fort A.P. Hill and 11 locations in the grass lanes at Fort A.P. Hill. For the data collection, instances of mine targets, false alarms, and cells with neither targets nor false alarms were laid out in a grid pattern. Tests were not blind regarding potential target location, but were blind regarding the actual presence of a mine or false target and its type. A number of mine types were available in the data collection, including the VS-50, M-14, M-19, VS-2.2, PMA-3, VAL-69, and 3-in. and 6-in. plastic simulants. Potential false alarms included a crushed plastic bottle, a plastic cap, tree roots, plywood pieces, and rocks. Data consisted of a series of eight time waveforms across the lane (each separated by an inch or so from the next), with the series repeated every few inches in the down-track direction. Typically, five down-track positions were used for a target, resulting in forty 250-sample time traces as the basic data to be used in algorithm development and testing.

Three types of analyses were performed. The first looked at the detectability of a single mine type at a known depth. The second analysis repeated the first, but with the mine depth unknown. The third analysis evaluated performance when all possible mines

could be present. The starting point for algorithm development was the likelihood ratio test, but that was extended to a conditional test, conditioned on mine type and on clutter models. Results presented were generally much superior to energy detector results under the same conditions. Because of the sparse data set, however, there was a problem segregating training and test data. In the one completely segregated test, training data for the VS-50 mine in bare soil was successfully used for a limited test of data in grass.

16. NEU Humanitarian Demining MURI Efforts on Clutter Modeling and Inverse Scatter Methods for GPR, *Northeastern University*

This work was carried out at Northeastern University (NEU) under the ARO MURI. Carey Rappaport gave the presentation on clutter modeling, and Eric Miller reported on inverse scattering research.

The reported clutter modeling effort focused on the effects of rough surface scatter on a standoff sensor. Results were produced using Monte Carlo FDTD modeling. The first simulation results presented showed the effects of a rough surface on distorting the single frequency return from a buried metallic mine. Higher frequencies were shown to improve detector resolution, but also to increase the clutter signal.

Extensive simulation output was also provided for impulse waveforms. The rough soil surface was modeled as having a bivariate Gaussian height density function with a Gaussian height autocorrelation function. Scattered waveforms were calculated for a large number of surface realizations, and statistics were presented for relative amplitude and delay for the scattered component and transmitted component. The level of time shift, amplitude scaling, and distortion depended significantly on the roughness statistics. Dispersion was found to be an important effect for time domain modeling.

The second portion of the NEU presentation examined shape-based inverse-scattering methods for mine detection. The difficulties inherent in this particular inverse-scattering problem are more formidable than those of the standard free-space inverse-scattering problem. Complications include the following:

- Near-field scattering with a planar interface does not allow a simplified forward model;
- The problem is nonlinear;
- It is ill posed; and
- A forward-model approach requires solution of a partial differential equation.

An implicit regularization approach was chosen using object-based, rather than pixel-based, reconstruction. Four examples were provided to demonstrate the inverse-scattering approach capabilities. In general, shape-based and limited-texture data could be recovered from limited scattered-field data using a low-order model. A perturbation-based “greedy solution” strategy was used to determine the parameters for the low-order model.

17. The Roles of Clutter and Signature Libraries in GPR Algorithm Development, *University of Missouri-Columbia*

Paul Gader described training-based signal-processing algorithms as applied to GeoCenters VMMD and CRC HSTAMIDS data. Most of the focus was on GeoCenters data taken at Aberdeen Proving Ground, Socorro, and Fort A.P. Hill. In an implementation of the Hidden Markov Model, mine states were modeled based on diagonals observed in the hyperbolic-shaped radar responses. Examples of results from several data runs were briefed, and typical performance numbers quoted included probabilities of detection around 0.80 coupled with *FARs* in the range of 0.02–0.04 per m². Comparison to results of the earlier ADT ATR used by GeoCenters (see summary of GeoCenters work) showed a reduction in *FAR* by about 25 percent for the same P_d . Application of morphological shared-weight neural networks to GeoCenters data taken in a variety of environments produced similar results. Work is planned to fuse the results of the two algorithms and extend the application to CRC HSTAMIDS data. This work is sponsored by the humanitarian demining MURI, the VMMD program through GeoCenters, and the Armament Directorate at Eglin AFB.

B. SUMMARY OF EXISTING RADAR SYSTEMS

In Tables II-1, II-2, and II-3 we provide a summary of several existing GPR systems. In addition to those radars described at the workshop, we also include parameters of other systems where they are known and publicly available.

Table II-1. Down-Looking and Forward-Looking GPR Systems

Contractor	Direction	Horizontal Aperture	Azimuth Process	Antenna Height	Frequency Band	Waveform	Polarization	Range
GeoCenters	Down	15 elements over 3.5 m	focused array	<0.5 m	0.7–1.3 GHz	impulse	linear—cross track	2 m
Marconi (ex-GDE)	Down	3 m	scanned elements	<0.3 m	0.4–2 GHz	stepped frequency		2 m
Mirage	Forward (Circle)	13-m dia. circle	SAR	13 m	0.02–1.2 GHz	gated FMCW	V	13 m
ARL	Side Looking	>10 m	SAR	>5 m	0.04–1.2 GHz	impulse	dual	7–20 m
Jaycor VMMD II	Forward	~3 m	pseudo interferometry	~2 m	0.5–4 GHz	stepped frequency	variable	~30 m
SRI	Forward	4 m	SAR	~4 m	0.3–3 GHz	stepped frequency	dual	7–60 m
Coleman	Forward	4 m	?	~3 m	2–2.5 GHz	stepped frequency	V	5–15 m

Table II-2. Operational Hand-Held or Cart-Mounted GPR Systems

Contractor	Direction	Horizontal Aperture	Azimuth Process	Antenna Height	Frequency Band	Waveform	Polarization	Range
Geo-Centers	Down		none			impulse		
Marconi (ex-GDE)	Down	~ 12 in.	none	2–6 in.	0.5–3, 4–6 GHz	stepped frequency	linear	
PSI	Down-looking Cart	33 in.	SAR	6–8 in.	0.8–2.0 GHz	stepped frequency	opposite circular pol T and R	
Wichman		~ 8 in.	waterfall time traces			impulse		
Coleman	Down	~ 12 in.	none	2–6 in.		stepped frequency	circular	

Table II-3. GPR Special-Purpose and Other Instruments

Contractor	Direction	Horizontal Aperture	Azimuth Process	Antenna Height	Frequency Band	Waveform	Polarization	Range
SRI airborne	Forward	4 m	SAR	~4 m	0.3–3 GHz	stepped frequency	dual	7–60 m
LLNL	Down-looking	1 m × 1 m	3-D images	surface	~1–4 GHz	impulse	n/a	-
CRREL	Down-looking	1.1 m	Image	near Surface	1.6–3.2 GHz	CW stepped frequency	PSM	-
OSU/ESL	Down-looking ATV		none	near surface	1–400 MHz	stepped frequency	PSM	-
OSU/ESL	Down-looking/ Cart		none	4–ft	1–6 GHz		linear	-

III. STANDOFF

A. FORWARD-LOOKING RADAR FOR COUNTERMINE OPERATIONS

The *forward-looking* (FL) GPR concept is quite specific in terms of mission, targets sought, expected clutter environment, and target illumination geometry. The mission is to support a multisensor vehicular mine-hunting system by providing standoff cues to buried and surface objects in the vehicle path, which could include individual mines, minefields, scattered submunitions, or other obstacles to military vehicle traffic. The standoff/remote-cueing capability could be used to locate high-threat objects in the direct vehicle path or lower priority objects off to the side of the roadway. Although achieving a high detection probability may require a concomitantly high rate of false cues, this could be supportable if a high-confidence discrimination system, which may be possible with nuclear quadrupole resonance (NQR) or thermal neutron activation (TNA), is available in the sensor suite. In particular, a forward-looking sensor with the ability to delimit large fractions of the field of view with high confidence could be used to significantly enhance the speed of advance of a slower confirmation sensor.

Before advocating research requirements for a forward-looking system, it is first important to make some judgment of its prospect for success. On the positive side, the signal-to-clutter ratio in the forward-looking case may improve over the previously tested down-looking case. The forward-looking viewing geometry will provide multiple looks at both targets and clutter, which may allow for better discrimination. Problems associated with gating out the surface specular reflection will also be eliminated. This is accompanied, of course, by the inability to gate out surface clutter that will need to be discriminated. Further, the low grazing angles associated with significant standoff will decrease ground penetration. On balance, we conclude the potential is sufficient to recommend a research program. This is especially true when one considers the dearth of other sensor options for the forward-looking standoff mission.

We identify a focused plan for conducting the necessary supporting research and obtaining needed engineering design data to support an operational concept for forward-looking stand-off GPR in countermine operations. The instrumentation to collect the necessary data will not serve the same purposes or be built to the same requirements as

the equipment fielded for countermine operations. We will generally want the test instruments to cover a wider range of operating parameters than we would anticipate using in a fielded system, so that we can be confident that the limits of the operating system are optimally chosen.

B. RADAR DESIGN ISSUES

For a vehicle-mounted, forward-looking radar the principal design elements and parameters are the following:

- *Intended target characteristics.* Size and material are the most basic characteristics to consider. Even at the most elementary level of processing, a radar resolution cell should be sized to capture all the target-scattered energy along with minimum clutter. Resolution consistent with multiple pixels on target may be required to sub-resolve the target as an aid to discrimination (there is evidence that this may be effective). Sub-resolving the smallest targets of interest (AP mines of diameter < 10 cm) will require resolution of a few centimeters.
- *Grazing angle at the target.* Clutter backscatter and ground penetration will vary significantly with grazing angle. Targets and clutter objects may also have different decorrelation properties with respect to changes in grazing angle. If verified, this could be used in clutter discrimination.
- *Viewing geometry.* Minimum and maximum range requirements affect the length of time a given object (mine or false target) will be under observation by a moving radar. Along with the antenna height, minimum and maximum range define the range of grazing angles available for observing the object. Minimum and maximum range will set requirements for the radar waveform, as well as other radar system parameters, such as power, and will determine cross-track resolution at maximum range. Antenna height is critical because it will govern the grazing angle at maximum operating range. A secondary effect of antenna height may be susceptibility to RFI.
- *Width of the real or synthetic antenna aperture.* The cross-track dimension of the radar resolution cells is critical for matching resolution to target size and for controlling the average clutter power with which the target signal must compete for detection.
- *Frequency range of radar waveform.* The bandwidth controls the along-track dimension of the radar resolution cell, while the absolute frequency will affect several factors, including soil penetration, resonant interaction with targets and clutter objects, cross-track resolution, and potential for RFI.
- *Average transmitter power.* Sufficient power is important in achieving clutter-limited performance, particularly in the presence of RFI.

- *Antenna vertical aperture dimension.* This affects overall system gain and sensitivity as well as possible susceptibility to RFI. It must be chosen consistently with the need to fully illuminate the range swath.
- *Ringdown time of the antenna and vehicle structure.* Unless ringdown is well controlled, or provision is made for effective cancellation, this phenomenon will limit system sensitivity at close ranges. This is particularly undesirable if grazing angle variations at close range provide some clutter discrimination or if steep grazing angles are required to achieve necessary ground penetration.
- *System instantaneous dynamic range.* Sufficient dynamic range is especially critical in a forward-looking countermining system because of the need for ringdown and RFI cancellation, as well as the large anticipated values of pre-processed clutter power that result from illuminating large physical areas at each position in the aperture. This is controlled by both analog circuitry and by the number of bits in the analog-to-digital converters.

C. EXPERIMENTAL DESIGN

The most likely terrain for the operation of a vehicle-mounted, forward-looking countermining radar would be roads and perhaps flat, off-road terrain. Roads provide a clutter environment that is clearly important to AT mine clearance and that may be relatively benign. Despite these considerations, there have been no programs directed to the specific goal of characterizing road clutter over the range of grazing angles and radar resolution cell sizes likely to be relevant to forward-looking radar systems. This suggests an opportunity to direct future data collection efforts. Further, because of potentially high RFI levels, the forward-looking radar may be ultimately noise limited, rather than clutter limited; this must be clarified based on data.

The forward-looking radar program may provide a data collection resource for some selected studies. Although limited by system design choices that have been made, some valuable data may be obtained from planned tests at little or no cost. However, a significant data analysis effort would need to be initiated. For example, although the SRI system provides large bandwidth, full polarization data, the initial data has been severely contaminated by ringing from the platform, and unless this is eliminated, close-in data from this system will not be useful. Ideally, a special-purpose research instrument should be constructed with as few constraints as possible. For either approach, experimental design should reflect the fact that clutter phenomenology is characteristic of the radar system as well as of the environment in which it operates.

1. Grazing and Aspect Angles

It is important to understand the variation of clutter and target scattering and decorrelation with grazing angle. A near-term, road-clutter, data-collection project would emphasize grazing angles in the 10- to 50-deg range, with the shallower angles of interest for detecting surface objects and the steeper angles of interest for detecting buried mines. Data would be collected on the *same* clutter and targets over the range of grazing angles so that any decorrelation could be observed. Likewise, data would be collected on at least some of the clutter patches over a range of aspect angles to investigate any decorrelation with these variables. Road clutter correlation should also be studied as a function of the direction of travel.

2. Road and Terrain Types

Road types should include a range of pavings such as simple unpaved dirt, unbonded and water-bonded macadam, and asphalt. Bear in mind that the ability to detect not only buried mines, but also surface mines, scattered submunitions, and other surface obstacles, is relevant. We will want to collect data not only from road surfaces, but also from flat terrain, both bare and vegetated, but the primary interest will be in terrains likely to support military vehicle traffic.

3. Target Types and Configurations

We want to use several types of mines and mine surrogates, with results separately tabulated. Besides buried and surface metal and low-metal AT mines, we want to look at surface-scattered mines and surface submunitions that aircraft, artillery, or battlefield support rockets could deliver quickly. As for clutter, we want to look at a variety of aspect and grazing angles and be able to study decorrelation with variations in angle. Because the FL system will inherently be able to observe possible targets over a range of grazing angles as it approaches, this phenomenology could lend itself to discrimination against clutter.

4. Spatial Resolution

Target/clutter discrimination schemes that exploit the ability to resolve individual target features require multiple resolution cells on each target. For simple energy detection, on the other hand, it is desirable to have resolution cells approximately matched to overall target image dimensions. Clutter statistics generally vary with the dimensions of the resolution cell. For these reasons we want to be able to process the data to variable

resolution cell dimensions ranging from at least the maximum size of AT mines down to the best resolution obtainable with the instruments in use.

5. Frequency Range

Beyond a general consensus that low frequencies penetrate better and higher frequencies give better resolution, there has been little consistency in the choice of frequency range made by the designers of GPRs. Some of these choices may be attributable to different intended uses, but in other cases, choices appear to have been based on the frequency support available from an antenna or impulse generator or by other operational factors. In addition, equipment designed for one mission is often used to conduct experiments aimed at another. The ARL BoomSAR and the Mirage circle-SAR cover the range from below 50 MHz to over 1 GHz. Other systems have been designed to operate with a low frequency limit in the 300–700 MHz range and with upper limits of 2–4 GHz or more in some cases. An extended upper frequency limit can be justified on several grounds: resolution, useful in discriminating mines from clutter, is enhanced by a large spectral support; spectral response, observed by the ARL team and others, requires that the resonant frequencies be excited, and for some mines these frequencies are several gigahertz (Ref. 1). Further, surface clutter may be suppressed using wideband waveforms that do not necessarily penetrate to reach the target, but that give a well-defined surface clutter background. Although an instrument for collecting engineering data need not meet the same constraints as a fieldable system, practical considerations of antenna size and technology will probably set a low-frequency limit at ~200 MHz or above. The upper frequency limit should be above 4 GHz, if possible.

6. Azimuth (Cross-Track) Resolution

The cross-track resolution achievable will be limited by the cross-track antenna aperture (real or synthetic), frequency band, and standoff range. There are several different methods for achieving this resolution, and there is no requirement that an experimental instrument and a fieldable system employ the same approach. An experimental data collection instrument should be based on SAR rather than an equivalently sized real aperture or set of apertures. Such a design choice minimizes the investment in a specialized wideband antenna, allows the flexibility of arbitrary degrees of spatial sampling or over-sampling, and permits alternative cross-range processing techniques to be tested, including variable cross-range resolution. The price paid for these advantages is a relatively slow data-collection rate. An operational system would, on the other hand, be

more likely to use an electronically scanned real-aperture antenna to maximize speed. This antenna would be more costly than a SAR system, but would be designed around the optimum performance parameters defined by the experimental program.

7. Polarization

Researchers have reported various effects associated with polarization (Ref. 2). Polarization parallel to the incident plane (vertical polarization) is associated with better soil interface penetration, but also with higher reported surface clutter levels. At steeper grazing angles, cross-polarized returns are reported to show improved signal-to-clutter ratio over copolarized measurements. From the standpoint of FL countermine operations, these points need to be established by collecting full-scattering matrix data on both targets and clutter.

D. EXISTING FORWARD-LOOKING RADAR SYSTEMS

Several GPR systems have been developed, either to support experimental programs or as prototypes for operational testing, with characteristics that are relevant to a forward-looking radar concept. The characteristics of these systems are briefly summarized in Chapter II. Those of GeoCenters and Marconi are variations of the down-looking radar concept. We can learn from the technology developed in the radar and antennas, but considerable investment would be required to adapt them to the forward-looking mission. The Mirage circle-SAR and ARL BoomSAR are ground-based systems developed to emulate the very large angular apertures associated with airborne data collection. The developers of both of these systems have shown plans to adapt them to forward-looking, ground-vehicle-based systems. In their current configurations, spectral support goes as low as 20–40 MHz. They are, however, limited to a maximum frequency of ~1.2 GHz, which falls considerably short of what is likely to be the useful maximum, so neither system probes the frequency space needed to determine such. Extending this upper limit is feasible on the ARL system. The current impulse generator and antenna will support frequencies in excess of 2 GHz, but the speed of the current digitizers will not. ARL is also exploring conversion to a stepped-frequency system.

The Jaycor, SRI, and Coleman systems have been designed specifically for the forward-looking stand-off detection role. The SRI system uses cross-track antenna motion to achieve a synthetic aperture for cross-track resolution. The attainable cross-track resolution is 5 cm at the closest range, and the resolution degrades with increasing range. To estimate the lateral location of potential targets, the Jaycor system uses a

pseudo-interferometric technique of registering downrange profiles from receive antennas spaced ~ 3 m apart. This technique leads to ambiguous target locations in highly cluttered environments. Details of the Coleman system's cross-range processing are unknown to us, but its resolution should be consistent with the aperture available in the cross-track dimension. The bandwidth of the Coleman system is significantly narrower than that of either the SRI or Jaycor systems and is probably inadequate for collecting complete data. It is uncertain how feasible it would be to extend this bandwidth.

E. TWO- vs. THREE-DIMENSIONAL SAR

For achieving cross-range resolution, SAR is certainly an acceptable processing alternative, particularly for the instrumentation system described above. This raises the question of collecting SAR data over a fully coherent two-dimensional aperture. In conjunction with the wide RF bandwidth this could allow us to process three-dimensional resolution cells. For the forward-looking case, however, a useful standoff range is not compatible with subsurface three-dimensional imaging. The reason for this is illustrated in Figure III-1. As the incident EM wave passes into the ground, where it encounters a change in refractive index, it is bent toward the surface normal according to Snell's law. For a diversity of angles at low incidence, the angular extent in the ground is severely compressed.

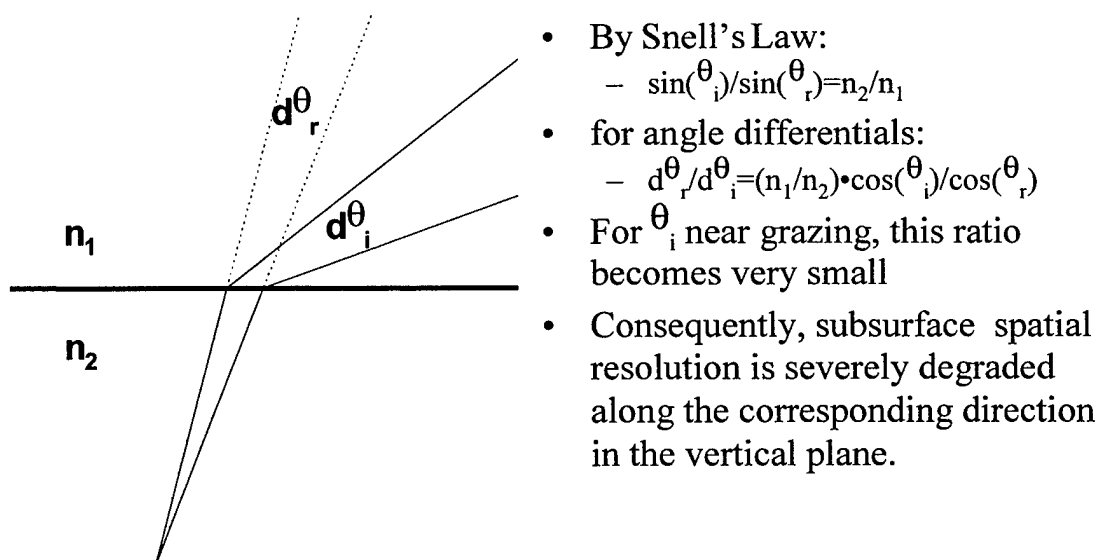


Figure III-1. Compression of Angular Spectrum

Figure III-2 illustrates this effect in the forward-looking geometry. The upper left frame shows a notional set of points collected to process a three-dimensional image focused at the point (0, 0). Refraction at the surface tends to compress the angular extent

of the wave number space (k-space) spectrum into a plane, as shown in the upper right frame, resulting in loss of resolution in the direction normal to that plane, and providing what is essentially equivalent to two-dimensional SAR. The two lower frames show a one-dimensional cut in cross range and a two-dimensional image in the down-range/vertical plane of the impulse response function of the point target. The poor resolution is evident in the lower right frame. Thus, there is likely to be little success in using three-dimensional processing to gate out surface clutter in this geometry. On the other hand, the down-looking SAR data collection geometry and process, discussed in Chapter VI of this report, could be used with effective three-dimensional processing.

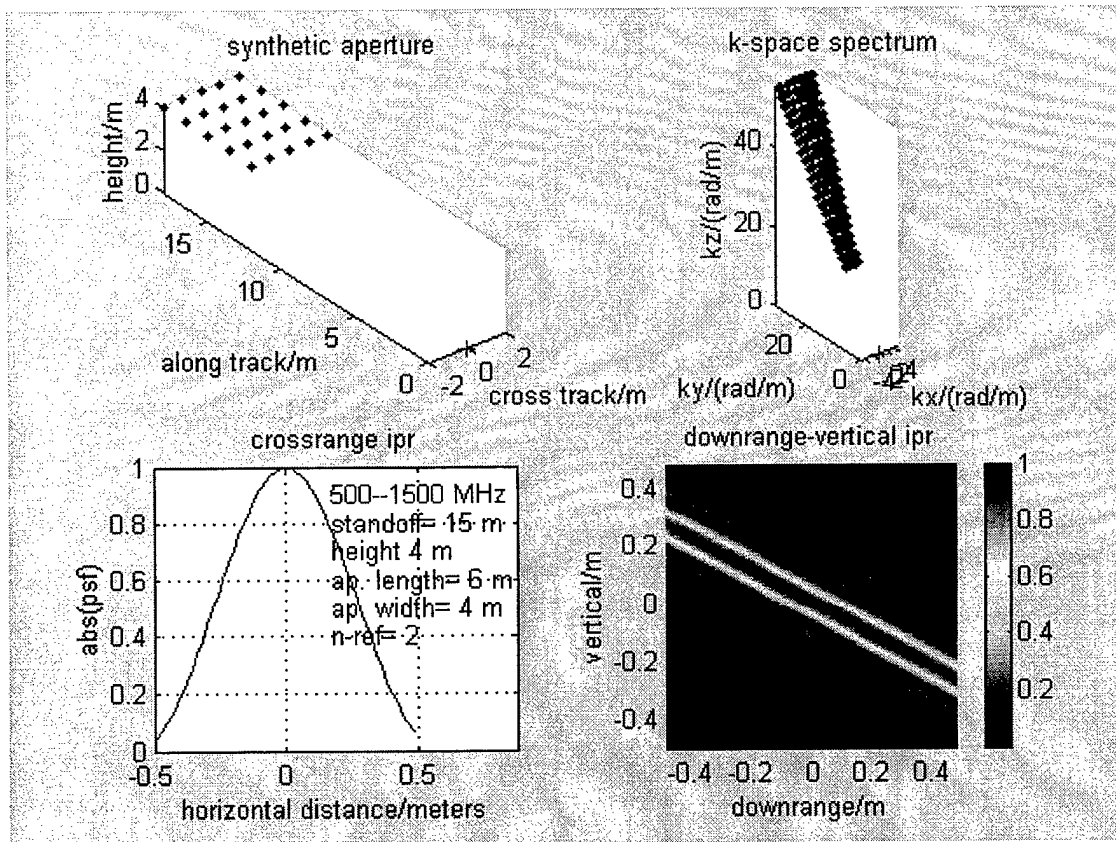


Figure III-2. Geometric Considerations for Forward-Looking Radar

F. AIRBORNE RADAR FOR CM/UXO

Another possible stand-off application is wide-area search from an airborne platform. The mission of an airborne sensor is likely to be for detection of concentrations of targets such as minefields, scatterable munitions, or impact areas contaminated with UXO. If the mission can be limited to groups of targets where modest P_d on individual targets is acceptable, a useful asset may be achievable. There is no baseline measure of

performance for any such mission, however, so predictions of success are premature. To date, no system engineering specifications have even been developed for an airborne SAR for mine or UXO detection, although a UHF SAR is currently being developed by DARPA for foliage-penetration applications.

The role of airborne radar in counter-mine/counter-UXO operations is likely to be limited, given the problematic results registered to date by ground-based systems. For a limited target set and operational concept, useful performance may be achievable. In order of increasing difficulty (but not necessarily importance), we consider the following missions:

- *Surface mines and scattered submunitions on roads.* Surface mines can be positioned quickly by opposing forces, and air- or artillery-scattered mines can be delivered almost instantaneously. Thus, there is value in the ability to conduct rapid all-weather searches for surface objects along potential travel routes. In this case, the most severe clutter source is likely to be the road surface or rare and well-defined discretes from natural or cultural objects, such as refilled potholes or depressions where water pools. Success of any ATR algorithms will likely require high resolution. For the detection of surface-only targets on roads, an X-band or Ku-band radar may be suitable, despite the inability of such systems to penetrate any but the lightest vegetation. Because the Army is currently developing an Ku-band SAR for use on the UAV, it would be reasonable to plan an early test of this system against surface-scattered munitions.
- *Surface mines and scattered submunitions in light vegetation.* For this case, the effectiveness of X- or Ku-band is likely to be limited. Additional experiments should be performed using the forward-looking testbed to probe frequency coverage requirements. We would expect performance to be significantly poorer than that achieved from X- or Ku-band searching on road, due to (probably) higher clutter and (almost certainly) poorer resolution. Such experiments will be a relatively inexpensive way to determine whether the development of a special lower frequency SAR for airborne use is warranted.
- *Other cases.* The feasibility of detecting buried metal and plastic AT mines in roads and lightly vegetated open areas with an airborne radar could be inferred from the tests planned for the forward-looking, vehicle-mounted radar and described above.

G. RECOMMENDATIONS

For the forward-looking program, a research-quality instrument should be built. Although we provide a strawman matrix for such an instrument and data collection, the

specifications of this platform should be subject to an extensive red-team effort to ensure that the broadest range of operating parameters possible is explored. This instrument should be tasked to do extensive data collections for both targets and clutter. A significant, concurrent data analysis effort should also be implemented.

For all future operational tests, raw data should be a deliverable to the government, along with appropriate systems specifications (calibration) and software for accessing the data. Further, specific contractor-executed, program-oriented analyses should be funded and deliverable to the government. At a minimum, such tasking would include histograms of target and clutter returns at feature and decision level or decorrelation analyses of target and clutter returns for multiple-sensor platforms. If a dedicated research platform is not built, existing forward-looking sensors should be considered for possible modification to improve data quality.

For airborne detection, the DARPA FOLPEN ATD sensor should be tasked at the earliest opportunity to acquire data for minefield and impact-area detection from an airborne platform. This could provide an initial, although not ideal, data base for algorithm development, as well as determine baseline performance in ground-truthed experiments. For airborne detection of surface targets, especially in roadways, the TUAV Ku-band SAR under development should be tasked at the earliest opportunity to test its potential.

A study of road structures should be undertaken. This survey should include methods of engineering, constructing and maintaining roads, as well as radar measurements on an appropriate subset of roads. Differences between foreign and domestic road construction should be examined.

A study of sensor requirements to support minefield and UXO impact area detection should be undertaken. The results of this study should be used to define system specifications.

CHAPTER III—REFERENCES

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IV. DOWN-LOOKING SYSTEMS

Directly down-looking systems are typically operated close to Earth's surface rather than in a vertical standoff geometry. The angular regime and the proximity of the antenna to a rough dielectric interface significantly affect operation, as well as the data required for system development and validation.

A. DOWN-LOOKING SYSTEM MISSIONS

Three possible operational roles for a down-looking system have been suggested:

- As a confirmation sensor on a vehicle system, where it must eventually compete with NQR, neutron activation, and trace detection sniffers, if they prove reliable. This application has received significant support and is mature in the sense that operational platforms have been constructed and tested.
- In hand-held devices, where weight and size constraints put severe limits on the sensors used and detection localization depends on physical proximity to the antenna. There has also been significant effort in development of systems and testing for this application.
- In a mission to identify or classify UXO, where maximum k-space coverage¹⁰ is required for feature extraction. The application of radar to this mission is immature and the likelihood of success is not evident.

The Army is currently funding system development for both hand-held and vehicle-based down-looking GPR. The performance of these systems in field tests has been limited by numerous clutter returns, thus indicating the most likely avenue for productive research efforts. The current HSTAMIDS and VMMD systems (Coleman and EG&G, respectively) could be used for limited clutter-characterization work; however, a purpose-built research-grade instrument to study the greatest accessible k-space is likely to provide far more useful data.

¹⁰ k-space is discussed in Appendix A.

B. k-SPACE COVERAGE

Because down-looking systems provide the maximum available k-space coverage, they could have their most important role in the provision of diagnostic data for defining target and false-alarm characteristics, validation of models, and data for application of signal-processing techniques. These experiments will establish a benchmark representing the best capability radar could provide. Suitable data can be degraded to simulate other systems with limited resolution in the three dimensions and examine performance degradation from the ideal that will result from operational constraints.

Historically, the problem for GPR has been discrimination of desired targets from false alarms. Chapter VI discusses techniques proposed for discrimination. A requirement of most discrimination techniques is limiting the volume of a resolution cell so that contributions to the signal in a cell from a target are not swamped by contributions from clutter. Given an adequate antenna design and sufficient two-dimensional spatial scan, down-looking systems, combined with synthetic aperture processing, provide the maximum resolution in three dimensions that can be achieved by a given bandwidth system. Figure IV-1, based on a simple model of a point scatterer beneath an $\epsilon_r = 4$ half space, provides an illustration of the resolution available. By virtue of their wideband operation, most GPR systems, can achieve good resolution in the range dimension. Real one-dimensional arrays, such as the GeoCenters system, can provide good cross-range resolution with appropriate processing. However, those systems limit resolution in the second cross-range dimension by using only their antenna patterns. To achieve good impulse response functions in both cross-range dimensions requires either a large two-dimensional array or synthetic-aperture processing.

Synthetic-aperture processing is accomplished by a transform of data from wavenumber space (k_x, k_y, k_z) to Cartesian space. The broader the support in k-space, the finer the impulse response in the transform space. Note from the k-space spectrum plot at the upper right of Figure IV-1 that the down-looking synthetic aperture provides very good coverage in k-space and hence narrow impulse responses. Actual coverage is limited by two factors. Obviously, k-space coverage is limited to the upper hemisphere by the geometry; however, a further limitation is the effect of surface refraction bending rays toward the surface normal and limiting the low-angle k-space coverage. Even that disadvantage may be overcome in a down-looking system whose antenna is dielectric filled and closely coupled to the earth. Contrast Figure IV-1 with Figure III-2 for a forward-looking system. There, the resolution in the second cross-range dimension is severely limited by the look-ahead geometry.

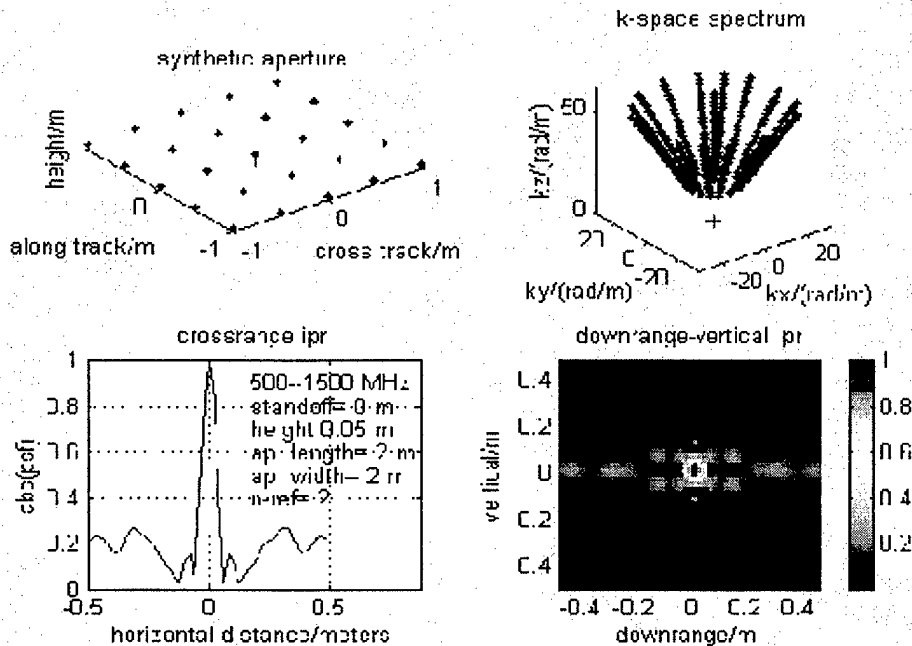


Figure IV-1. Predicted Impulse Response Function for a Three-Dimensional, Down-Looking SAR and a Simple Homogeneous Earth with $\epsilon_r = 4$

C. DOWN-LOOKING SYSTEM CHALLENGES

To be effective in a diagnostic data-collection role, down-looking systems must overcome a number of problems. While the down-looking geometry potentially provides the widest coverage of k-space, it also presents a number of challenges for the system designer. First and foremost, the large specular reflection from the surface of Earth creates the need for a wide dynamic range receiver, among other problems. This is particularly true for stepped-frequency or chirped systems, but it is even the case for impulse systems because of the short time available for recovery from saturation.

Poor antenna matching can cause multiple reflections between the antenna and surface (or within the radar itself), and such “ringing” can hide target returns. Other problems caused by the proximity of Earth’s surface, particularly for diagnostic systems that must be well characterized, are distortion of the antenna pattern and near-field effects. Both make it more difficult to predict what the GPR should see and hence make more difficult the interpretation of results. Thus, antenna design and characterization should be the subject of significant study for not only a data-collection instrument, but for any close-coupled, down-looking fielded system.

D. RECOMMENDATIONS

A large number of down-looking GPRs have been built over the years, both to meet data collection needs of scientists and as potential operational systems. Lessons learned from such systems can be valuable in guiding the design of new instrumentation systems capable of collecting data needed for understanding the limitations of GPR for mine and UXO detection. For example, the Wichmann radar clearly shows the advantages accrued from careful design of the antenna to reduce internal reflections. Previous fieldable (as opposed to laboratory) instrumentation radars, however, mostly predate the advent of digital frequency synthesizers and high-speed analog-to-digital converters. For those reasons, their frequency coverage was generally limited, as was their dynamic range. They did not employ a precise two-dimensional scanning mechanism that allowed for the possibility of three-dimensional imaging. Our understanding of the phenomenology of GPR has improved significantly, as have the hardware and software capabilities for producing and exploiting data. For that reason, new instrumentation systems that can provide the data needed by those designing algorithms for detection and discrimination and that have maximum flexibility for data collection and output are required.

In that regard, the Army should develop and build an instrumentation-quality down-looking radar with the following characteristics:

- Wideband operation (<200 MHz to >6 GHz)
- Two-dimensional scan mechanism suitable for synthetic imaging
- Well-matched antenna system and provision for substituting antennas for specific bands
- Ability to operate closely coupled to Earth's surface
- Wide dynamic range (>90 dB)
- Preferably capable of full polarimetry.

To provide useful information, particularly for shallowly buried mines, the surface clutter must be successfully removed. Close coupling of the antenna is one technique to do this; coherent subtraction techniques have been successful in certain cases. In any event, because removal of the surface clutter is not a straightforward problem to solve, it is an argument for systems operating off-normal incidence. In addition, antenna near-field effects must be understood to correctly interpret the data.

The mission of the system would be to collect exhaustive data over a limited area for target, clutter, and false target characterization and to provide data for model validation and signal-processing research. The advantage of such a system is that with

careful design and after careful characterization, it could provide the maximum amount of information available from any radar. In addition to showing the bounds of what could be achieved by certain signal-processing techniques, data could easily be degraded to show the limits of particular system concepts.

The applicability of existing systems to the data-collection mission is limited by previous choices of operating parameters. Nevertheless, as these systems continue to be developed and tested, the available data should be exploited. The government should embark on a program to characterize these systems. Raw data should be a deliverable to the government for all future tests. Specific analyses, such as the target and clutter statistics and sensor correlations described in Chapter III, should be performed.

V. SOIL CHARACTERIZATION

A. BACKGROUND

Between 1989 and 1994, as part of its ultra-wideband radar technology development program, DARPA conducted an investigation of GPR as a means for detecting buried mines as well as inhabited underground facilities. This work incorporated both theoretical and experimental activities and concluded that although the results obtained continued to demonstrate fundamental feasibility, the performance achieved fell short of desired goals. A careful consideration of the results obtained led to several important conclusions. The most significant was that the characteristics of the propagating medium are critical in limiting radar performance. Moreover, it is not simply bulk constitutive parameters (complex ϵ and μ), but the detailed *structure* and *inhomogeneity* of the soil that must be considered (Ref. 1).

There have been many studies of the dielectric properties of soils and rocks (see Refs. 2, 3, and 4 for some examples). The authors have carefully determined dielectric variations with soil and rock type including the effects of moisture content, and attempted correlations of electric and mechanical properties such as density. These investigations are adequate to support studies of the radar reflectivity of soils and minerals, and of the attenuation of RF energy with depth in various materials. Universally, however, these references treat the permittivity as a constant of the material rather than as a quantity that exhibits spatial variation. Without some understanding of inhomogeneous variation within soils, it is impossible to understand or predict the scattering of plane waves, which are critical to imaging of subsurface objects.

Inhomogeneity in the propagating medium is particularly important because of its impact on image-based target recognition processing. Image formation algorithms depend on the existence of a coherent phase relationship between every point in the synthetic aperture and every point in the image. This phase relationship must be determined solely by the known spatial geometry of data collection. Randomness in the propagating medium degrades this deterministic phase and will, depending on its level and scale, have a critical impact on image quality, leading to both image distortions and loss of contrast.

EM wave propagation in random media has been treated in the literature, generally from a statistical standpoint (Refs. 5, 6). For the most part, this theory has been applied to media whose departure from homogeneity is relatively small. Such media include sparse distributions of discrete particle scatterers and media with only small variations in constitutive parameters about the average. That is, media characterized by:

$$\frac{\epsilon - \langle \epsilon \rangle}{\langle \epsilon \rangle} \ll 1 \quad ,$$

where ϵ is the local value of permittivity and $\langle \epsilon \rangle$ is the mean.

Unfortunately, neither of these limits applies well to general underground propagation. There is consequently a need for additional fundamental research in the phenomenology of EM wave propagation in dense spatially random media. Particularly, this characterization needs to be done on spatial scales of interest for mine/UXO detection. This research should not be confined to statistical approaches. Modern computers and algorithms are capable of numerically computing propagation through specific realizations of "randomly" nonuniform media. Such model experiments can be compared with real measurements and used to shape the development of statistical theories.

To include spatial fluctuations in our description of soil dielectric properties we need to include two additional categories describing the relative magnitude of the fluctuations and their spatial scale or correlation lengths. These new categories are not simple dimensions. Because the permittivity is in general complex, variance must be considered in two dimensions (real and imaginary, or magnitude and loss tangent). Likewise spatial correlation lengths would generally be different in three dimensions. As an initial start, it may be sufficient to consider only fluctuations in the real part of the dielectric constant. Likewise, although we would expect spatial correlation lengths to differ between vertical and lateral dimensions, we could begin with a simple model taking the same value in all directions. Exhaustive study of all soil conditions is certainly not feasible; however, it should be possible through careful selection of a large but finite set of experiments to characterize statistically a broad range of conditions that could be used to bound expected radar performance.

B. CURRENT PRACTICE

Although in principle the effect of the soil on radar propagation is completely specified by the constitutive parameters, $\epsilon(x,y,z)$ and $\mu(x,y,z)$, there is as yet no satis-

factory set of experimental techniques for determining those parameters in undisturbed native soil. Current practice in soil characterization is either to send soil samples to a laboratory for measurements of bulk-averaged constitutive parameters or to attempt these measurements in place using a variety of RF probe instruments. Both of these procedures have serious drawbacks. Collecting samples for lab measurements disturbs the soil's native structure and generally changes the water content as well. The resulting measurements generally only bracket the average parameters of the medium in situ and do not reflect any inhomogeneity effects. On-site probe measurements account for actual water content, but have not been developed beyond simple measurements of dielectric constant and effective conductivity. With such instruments spatial variations are averaged over the the range of the fields used in measurement and spatial inhomogeneity can only be roughly characterized on the length scale of the spacing between probe measurements. Such measurements tend to be made only over the surface, so variations with depth are difficult or impossible to determine. It should be possible, however, to obtain indirect data relevant to spatial fluctuations by exploiting the sensitive impact such fluctuations have on image quality. This is discussed further below.

C. RESEARCH REQUIREMENTS

At present there has been little or no attempt to apply the same statistical characterization methods to soil media that have been applied to atmospheric refractivity variations to describe radar and laser propagation. Besides the issue of the density and variance of soil parameters, additional difficulties arise because for soils in place we generally have only one-sided access to the media of interest, limiting us to back-scattering measurements. Moreover, soils, unlike the atmosphere, are relatively immobile, complicating attempts to collect statistically significant numbers of measurements on a well-defined ensemble. Whereas the fluid atmosphere can be statistically sampled by a single probe, similar statistical samples of the soil will require moving the probe.

To summarize, our understanding of soil effects on EM propagation will be improved by research in three areas:

- *Statistical Descriptions*—Starting from basic available theory that has been developed to describe the effect of atmospheric effects on EM propagation, attempt to extend these results to soil media. This is not trivial, in that soils show a much larger range of variation in constitutive parameters than the weakly scattering, diaphanous media for which much current theory has been specialized (Refs. 5, 6), and the spatial correlations of variations in soil

parameters are likely to be very different from those in atmospheres. Nevertheless, existing theory is a good place to begin.

- *Numerical Modeling*—This will involve the construction of a computer-based simulation of the propagation and scattering of EM waves due to both targets and clutter in realistic inhomogeneous soil structures. This simulation will include the ability to model both metallic and dielectric targets of various shapes, variations in soil permittivity on a variety of scales that are either random or spatially correlated in one or more dimensions, and variations in surface morphology and cover.
- *Measurements*—Two different kinds of measurements are desired. The first set will be accomplished in situ in various soils and surfaces (e.g., roadways) of interest, the purpose to measure a set of parameters going beyond the standard ϵ and μ to characterize soil inhomogeneity in terms of statistical measures to be developed in phase 1. The purpose of the second set of measurements is to acquire data needed to validate the numerical models described in phase 2. Phase 3 may include developing a scale-model laboratory test bed at an existing EM research facility to validate the results of the simulation and extend the results to regimes where simulation may be impractical. For the immediate future, until experimental techniques are devised for measuring the constitutive structure of natural soils in place at the scale of a radar wavelength, it will be easier to work with a laboratory soil test bed. In the past, however, measurements made under ideal laboratory conditions have sometimes led to misunderstandings about real-world system capabilities, and we must be careful to ensure that laboratory measurements are relevant to practical media.

Because of the intimate connection between propagation and image quality, a technique for characterizing soil inhomogeneity could be based on holographic imaging of a small, unresolved target over a large spatial aperture. This would allow the impulse response of the synthetic aperture radar to be measured as a function of the content of the intervening medium, which can be varied over a range of host materials and inclusions. By measuring the departure of measured target phase from that projected on the basis of the deterministic experimental geometry, we can obtain data to compare with the predictions of statistical theory. Figure V-1 shows an example of such an experiment.

Once this apparatus has been baselined and shown to give useful results with laboratory-constructed soil mixtures, it can be extended to more practical cases. Two examples would be the omnipresent dirt or unbonded macadam road of interest for AT mine detection and examples of the soils in which AP mines would be hunted. It would

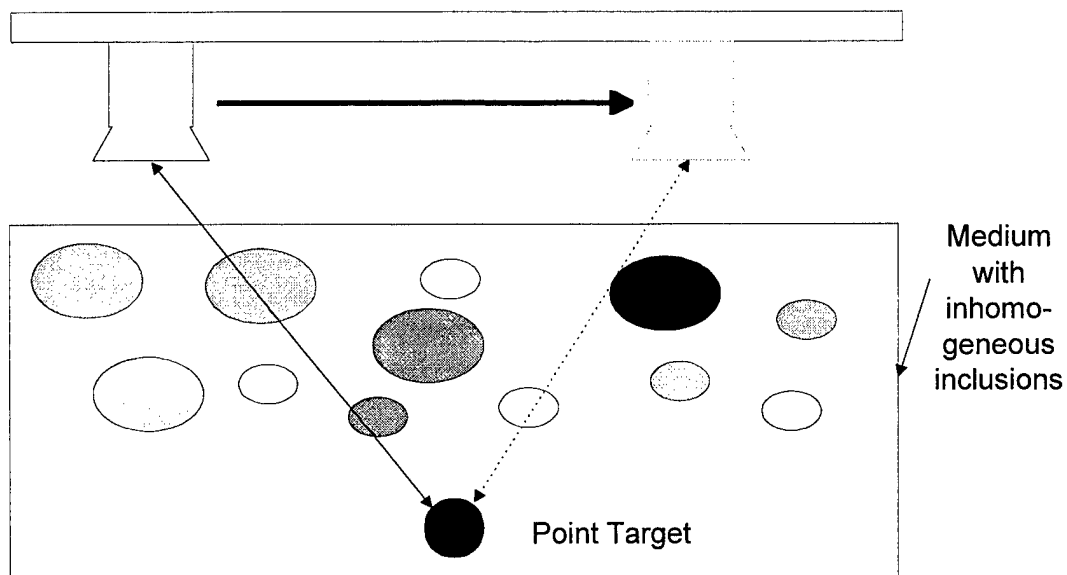


Figure V-1. Characterization of Soil Inhomogeneity Using Holographic Imaging.
In an ideal homogeneous medium the phase of the target return is determined by the scanning geometry. The departure of the measured phase from the deterministic prediction can be compared with the prediction of statistical theory as well as numerical modelling.

be practical to construct a section of a dirt or macadam road in a test box over a sample point target as outlined above and determine the impact of that specific medium on image quality. In that way the practical medium could be related to the laboratory-constructed media.

A second specific yet practical example would be the Aberdeen, Maryland, turf characteristic of the site used for HSTAMIDS testing. Ideally, a large section of turf, extending in depth to below the burial level of AP mines, would be excavated intact and emplaced over the standard scattering target. Again, observations of image impact would permit the practical soil case to be calibrated in terms of the laboratory-constructed cases. Besides providing a calibration scale for practical natural media, this set of experiments would provide an experimental estimate of the GPR image quality to be obtained under the best of conditions.

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VI. DISCRIMINATION

It is only in very rare cases that GPRs searching for mines are noise limited.¹¹ As noted in the introduction to this report, clutter is the problem. Hence, successful discrimination of mines from other detected objects is the key to useful performance. Several discrimination techniques have been proposed:

- Late-time complex natural resonance
- Third harmonic techniques
- Image-based discriminants
- Spectral pattern identification
- Polarimetric processing.

The state of progress for each of the classes of techniques is discussed separately below, and areas for further research are identified.

A. RESONANCE-BASED DISCRIMINATION

Here, resonance refers to late-time effects. Useful responses are characteristic of moderate or high Q structures and are therefore inherently narrowband effects. A wideband signal may be necessary to excite such effects, however, because of uncertainties in the exact frequencies at which maximum responses occur for particular targets and the variability in soil conditions.

For conventional free-space radars operating in a noise-limited environment, the problem with late-time discrimination techniques has always been the low amplitude of the late-time return compared to the early-time response used for detection (typically 30 dB or more lower). Such relative amplitudes delay discrimination until the range to the target is 20 percent of the detection range or less. GPRs for mine detection tend to be clutter limited, so resonance-based discrimination may have more potential in this arena.

Of current efforts briefed at the GPR Workshop, only Ohio State University presented work in the resonance detection area, and that was related to UXO natural

¹¹ The forward-looking case may be a counterexample, as noted in Chapter III.

resonance signatures. Recently, others have published on modeling the resonance of buried mines (Ref. 1).

There are several questions regarding resonance-based discrimination:

- For various target types in various backgrounds, what is the ratio of the early-time to late-time returns? Is practical system sensitivity sufficient to detect these late-time returns?
- What frequencies are required to excite those returns for various targets of interest?
- How do those returns differ from those of natural and man-made clutter objects that produce false alarms?
- How robust are the resonant responses with respect to soil context, as well as variation in ordnance details?

Only recently have numerical models sophisticated enough to adequately explore such questions existed. These models provide an excellent tool for investigation of resonance effects; however, the results of initial modeling work on mine detection reported by Duke University do not appear promising for cases of practical interest (Ref. 2).

Based solely on the fact that signal amplitude for late-time resonance will be only a fraction of a percent of the early-time return, we anticipate little practical applicability in real-world conditions. Early modeling results support that expectation. Therefore, we do not recommend further research support in this area. If, however, further support is provided, a staged-modeling effort is recommended, supported by very limited measurements. The modeling effort should be specifically designed to explore the magnitude and robustness of the late-time return for the range of conditions expected operationally.

B. THIRD HARMONIC DETECTION

When excited by a radar wave, some targets radiate energy at the third harmonic of the incident frequency, as well as at the incident frequency. This nonlinear behavior is thought to arise from junctions between metallic structures that do not have good electrical contact. SRI reported work in the UXO area attempting to exploit the third harmonic signal. The advantage of such a technique is that the received signal is noise, not clutter, limited. The disadvantage is the weak signal strength obtained. Because the effective RCS at the third harmonic is proportional to the cube of the incident field, the radar range equation shows a behavior that it proportional to R^{-8} . Although this technique is of theoretical interest, the mechanism giving rise to the response is not robust (tens of

decibel variations in signal strength between two measurements of the same object were reported by SRI), signal levels are low, and we judge the results to date sufficient to conclude that the technique will have limited practical value. Therefore, we do not recommend further funding for research in this area.

C. IMAGE-BASED DISCRIMINATION

Radar spatial resolution is typically defined in the range and two orthogonal cross-range dimensions. For all radars, the range resolution is a function of the radar bandwidth, where the fundamental formula for resolution is $\Delta r = c/2B$, where c is the speed of light and B is the radar bandwidth. In real aperture radars, the cross-range resolution dimensions are controlled by the beamwidth in the two dimensions at the target range. Common radar usage often describes the return from a wide-bandwidth, real-aperture system as a one-dimensional image. That is, through wideband processing the radar achieves high resolution in one dimension. If a synthetic aperture is then formed in one of the cross-range directions, the resulting processed output is described as a two-dimensional image. Finally, if synthetic apertures are generated in both cross-range dimensions, the result is called a three-dimensional image. Appendix A provides a more complete explanation of radar terminology in this regard.

Currently employed wideband discrimination techniques are most often related to the ability of frequency diversity to provide improved resolution in the range dimension (produce a one-dimensional image). However, as noted above, frequency diversity can be combined with angle diversity in one or two dimensions to provide two-dimensional and three-dimensional images. In all cases, the goals are to provide smaller resolution volumes to allow characteristics of the target that are different than clutter to dominate the return in the resolution cell and even to collect multiple resolution cells on target. Questions which arise include the following:

- What is the optimum frequency band for a particular target/soil type/soil condition/burial depth?
- For realistic geometries and soil conditions, what point spread or impulse-response functions can be obtained for one-dimensional, two-dimensional, and three-dimensional images?
- What improvements in performance are obtained for two-dimensional imaging compared to one-dimensional imaging?
- What improvements in performance are obtained for three-dimensional imaging compared to two-dimensional imaging?

- What are the false alarm mechanisms of most concern for each imaging architecture?
- What signal-processing techniques are optimum for each architecture?
- What performance loss is incurred by suboptimum processing techniques that are less computationally costly than optimum techniques?

Historically, wideband waveforms and one-dimensional images have been the mainstay of GPR processing. Thus, the state of the art has progressed further in that area than any other. Most often, radars or their operators have basically employed “blob” threshold exceedence detection in one-dimensional profiles, although many experienced operators likely perform some form of heuristic pattern recognition. Research using more sophisticated signal processing is now underway. An example is Prof. Collins’ work at Duke (Ref. 3), where Wichmann GPR data is being applied to a conditioned likelihood ratio test. Significantly better false alarm performance is obtained than with a simple energy threshold test.

Either multiple real apertures or synthetic aperture techniques can be used to form two-dimensional images. In fact, the Wichmann system forms a limited two-dimensional image using eight traces from closely spaced antennas in a down-looking configuration. The GeoCenters system uses a more sophisticated real-aperture system, where the time delay for an impulse waveform is adjusted on transmit and receive to coherently sum the return from a pixel. In contrast, the ARL BoomSAR builds a synthetic aperture by moving the radar to create an aperture parallel to the direction of motion. The current major limitation of the boom SAR is that it only covers a frequency band of 40 MHz to 1.2 GHz. Recent studies by Duke and others indicate that frequencies higher than 1 GHz (possibly up to the 4- to 6-GHz range) contain information that may be useful for discrimination for small plastic mines. Similarly, SRI has implemented traditional two-dimensional SAR systems in both aircraft and ground platforms.

Three-dimensional imaging requires that an aperture be formed in both cross-range dimensions. Any of the two-dimensional down-looking measurement systems can create an unfocused third dimension in their images by simply creating a waterfall of two-dimensional images as the radar perpendicular is moved to the array. The localization in the second cross-range dimension is then a function of the discrimination provided by the antenna pattern in that direction. An example of this is the GeoCenters radar. A three-dimensional aperture can also be formed by coherent processing. Figure IV-1 illustrated predictions of the point spread function for a near-ground down-looking system providing a three-dimensional SAR image. Note that very good resolution is

provided in all three dimensions. Obviously, the ideal situation would be look-ahead three-dimensional imaging. Unfortunately, as noted in Chapter II, the physics limits what can be done in that regard.

D. SPECTRAL RESPONSE OF EARLY-TIME RETURN

A wideband waveform can be used to look for particular spectral characteristics typical of targets. An illustration is the work reported by ARL, where a spectral dip around 500 MHz was typical of radar return from a particular mine but not that of clutter. Modeling indicates that the early-time spectral pattern results from constructive and destructive interference of reflections from the front and back mine surfaces. Since the temporal and spectral responses from an object have a Fourier transform relation to each other, no additional information is available from the spectrum that is not in the temporal wave form. However, processing and discrimination algorithm applications might be more efficiently carried out in one domain rather than the other and thus there is value in exploring early-time spectral characteristics. Recent calculations by Duke predict that characteristic features in the spectral response of some small dielectric mines will be observed at frequencies well in excess of the current 1.2 GHz limit of the ARL BoomSAR, which to date has provided the measurements exploring that response.

Questions which arise include the following:

- What is the variability for a given target type in the spectral response for different soil types and burial depths?
- What is the variability among different mine types?
- How do these distributions differ from naturally occurring and manmade clutter?

E. POLARIMETRY

Radar as a military sensor has several disadvantages, of which two are primary:

- The requirement to transmit allows potential detection of the sensor, and
- Received power in a free space environment varies as R^{-4} , rather than the R^{-2} typical of passive sensors.

Neither of these, however, is a particular disadvantage in the countermine or UXO scenario, and there is the distinct advantage that radar allows the sensor designer to choose a waveform that optimizes performance. Part of that choice involves polarization. The most general choice is to sequentially transmit two orthogonal polarizations and

simultaneously receive both polarization components. When done with a coherent radar, the polarization scattering matrix (PSM) is obtained, and the PSM provides all of the information available from the chosen waveform. Thus, as additional information that might allow better discrimination between targets and clutter is potentially available in the PSM, polarization processing might be attractive for the countermine mission. In fact, polarimetric processing for target discrimination has shown itself to be valuable in other radar applications, particularly stationary target discrimination. Currently, limited polarization exploitation (e.g., transmitting one linear polarization and receiving the cross-polarized component to reduce surface clutter return) is often used in GPR. Full polarization processing, however, is not, because adding a PSM capability to systems exacts a significant price in equipment complexity and cost, and the real advantages are as yet unclear. For that reason, the use of sophisticated polarization processing for countermine and UXO applications is still in its relative infancy. Nevertheless, several avenues of potentially fruitful research are underway.

Bodies of revolution, when illuminated by a source polarized in their plane of symmetry, have no cross-polarized return. Initial ARL BoomSAR measurements and accompanying modeling results by Duke University for mines indicate that the symmetry of most mines provides a lower level of depolarization than do false targets, and that fact can be used as a discriminant. Measurements and modeling by Ohio State University for UXO indicate that polarization properties can provide length-to-diameter ratio information. In both cases, results are preliminary, and a wide range of false alarms has not been explored. Nevertheless, polarimetric processing must be further explored for its potential in the discrimination arena. Although a more complex antenna is required, there is enough potential discrimination enhancement to recommend that full polarization scattering matrix be part of future data collects to support system developments.

Questions which arise include the following:

- What amount of relative tilt of the source and mine target is required to produce significant cross-polarized return (degrading discrimination)?
- What amount of polarization isolation within the GPR is required and achievable?
- What are the depolarization characteristics of a sampling of false-alarm sources?

F. RECOMMENDATIONS

With rare exceptions, GPRs are capable of detecting mines. That is, the signal-to-noise level is large enough for detection. Thus, discrimination of clutter and false targets is the key to GPR utility in the counter-mine and UXO arena, and a large portion of the research in GPR for counter-mine should be focused on the discrimination problem. A better understanding of potential discriminants, gained through modeling supported by careful and accurate measurements, is necessary before innovative signal-processing solutions appropriate for those discriminants will be fruitful.

Increasingly sophisticated electromagnetic models can provide a critical link between measurements and theory to understanding mine scatter phenomenology. It is important that possible discrimination techniques be modeled for realistic counter-mine situations.

In pursuit of those objectives, we recommend the following:

- Continue development and validation of sophisticated EM models as discussed in Chapter VII.
- Collect carefully calibrated data containing typical target and clutter signatures for signal-processing research. These data should be a superset of the parameter space desired operationally. That is, the data should cover a wider frequency band and cross-range angular space than would be used in practice and provide all of the polarimetric information that might be used in practice. Some versions of both look-ahead and look-down systems should be employed. Data should be recorded in a format that allows degradation of resolution in any dimension. This likely argues for two-dimensional scan systems with stepped-frequency waveforms.
- Continue support of discrimination research based on modern signal-processing techniques.

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VII. MODELING

Modeling will be an indispensable tool in future developments for the application of radar to the mine and UXO problem. By probing the trade space of various parameters models can assist in system design. If realistic, modeled data can augment measured data for algorithm development. Models that have been convincingly validated can even be used to project system performance in environments for which experimental data is lacking.

The complexity of the electromagnetic environment associated with mine or UXO detection renders simple analytical models nearly useless for the prediction of behavior in realistic situations. Thus, the recent focus in modeling has been on numerical electromagnetic codes. Currently, that general area is one of fruitful research and rapid change. Military requirements and concomitant funding for the design of complex, low-observable platforms and the prediction of their radar cross-section performance over broad frequency ranges have greatly increased the sophistication of general numerical modeling techniques. Techniques originally developed in the aerospace arena [for example, FDTD and fast multipole methods (FMM)] have now been modified and generalized to handle the countermine and UXO problems. In addition, the Moore's Law¹² driven increases in computer capabilities, along with improvement in code sophistication, has allowed increasingly complex problems to be tackled.

Because numerical electromagnetics capabilities are changing so rapidly and research and capabilities are so widespread, no attempt will be made here to catalog available codes or discuss their current capabilities. Instead, general themes in code capabilities, along with examples of those capabilities presented in the workshop, are discussed.

As noted in workshop presentations by Duke University, Northeastern University, and the Georgia Institute of Technology, the level of sophistication in modeling the counter-mine and UXO problems has increased significantly over the past few years. Part

¹² Moore's Law holds that the logic density of silicon integrated circuits doubles roughly every 12 months. "This held until the late 1970's...at which point the doubling period slowed to 18 months." Source: http://www.netmeg.net/jargon/terms/m/moore_s_law.html, 25 October 1999.

of the improvement is due to the ability of computers to handle larger problems formulated with numerical techniques such as MoM and FDTD. Those techniques embody all of the physics inherent in Maxwell's equations, and insofar as numerical procedures are applied correctly to well-modeled problems with correct boundary conditions, they should turn out near exact answers.

Special-purpose codes, such as the body of revolution (BOR) MoM code employed by Duke, take advantage of known target characteristics to handle larger problems. For example, increases in computer power, combined with intelligent coding, have allowed Northeastern to do Monte Carlo modeling of surface roughness using their FDTD code. Similarly, Georgia Tech has done detailed studies of antenna design for minimum internal reflections and ground coupling. Nevertheless, these techniques are all plagued by the problem that computation time increases with (at least) the cube of the number of unknowns (and unknowns increase with the square or cube of the frequency) and thus the number of unknowns is limited. The major concern with such limitations is an inability to include a large enough volume to encompass all of the types of clutter, false targets, and subsurface structure that might be desired for training and testing discrimination algorithms.

More recently, a number of organizations involved in the aircraft RCS arena have developed FMMs to greatly increase the number of unknowns that can be handled on a given size computer. Duke presented results using its two-level FMM code, where computation time increases only as $N^{3/2}$, where N = the number of unknowns. Ultimately, implementation of multilevel FMM could lead to computation speeds proportional to $N \log(N)$.

A. MODEL INPUT DATA

The ability to successfully calculate EM interactions with complex scenes is only a part of the modeling problem. Equally as fundamental is knowing what to model and to what level of fidelity. That is, as we increase model complexity from the simple case of a mine buried in a homogeneous dielectric half-space, what things do we include and what are the physical and electromagnetic properties of the things to be included? Targets are relatively straightforward in that regard, as they are limited in number and, although they can be complex, well defined.

That is not the case, however, for the remainder of the surface and subsurface environment. At present, the capability in EM modeling has outstripped our ability to describe the environment we need to model. That environment must be adequately

understood and quantified before model output has any practical meaning. That is not to say that model predictions of simple media are not important and useful—such predictions can be key in recognizing target-scattering characteristics and in assessing how those characteristics change with changing environmental conditions, such as water content. To support discrimination algorithms, however, models eventually must exhibit sensitivity to all the details inherent in measured data. That will require a better understanding of the characteristics and inhomogeneities of the subsurface environment, including both a statistical description that accurately portrays the surface and subsurface characteristics and an understanding of false target discretizations.

B. MODEL OUTPUT

One problem with methods such as MoM, FDTD, and FMM is that they are essentially numerical experiments. That is, they provide the same results as the experiment they model, but no inherent understanding of the underlying physics. If data are collected carefully and analyzed correctly, however, numerical codes can provide enormous amounts of understanding of the processes involved.

Data from models may eventually be used by people other than the researchers who ran them. For that reason, it is critical that unprocessed, as well as processed, output be available for analysis. Particularly for discrimination algorithm development and testing, access to the raw data is critical.

C. RECOMMENDATIONS

If discrimination is the key to successful implementation of GPR for counter-mine or UXO, modeling may be the area that most efficiently permits successful discrimination research to go forward. The uncertainties in GPR measurements, even in relatively well-controlled environments, argue for a bridge between the theory and measurements, and numerical modeling can be that bridge. The keys to success in the modeling area are recognizing the environment to be modeled and ensuring that results carefully approach the “real world” in steps that allow parameters that affect results to be understood. In that regard, we recommend the following:

- Modeling should be implemented as an integral part of discrimination algorithm development and system design.
- Significant effort should be put toward accurately determining the subsurface environment for model improvement (as long as we don’t know how to define the subsurface, we don’t know how to model it).

- Carefully calibrated measurements of well-understood environments with increasing levels of complexity should be available for model validation.
- Include raw modeling data with analysis reports as a resource for other researchers.

VIII. FUSION

Even with optimistic projections of sensor capability, it is not likely that stand-alone radar will provide robust detection of mines and UXO at reasonable *FARs* across the spectrum of threats and environments of interest. It is more likely that radar will be one sensor in a suite of sensors. Its role could be as a forward-looking cueing sensor that may require confirmation from a complementary close-in sensor such as a metal detector or NQR spectrometer. Alternatively, radars could be employed in both forward-looking cueing and top-down confirmation roles, perhaps with a third sensor for additional clutter suppression. Making sensor selections and developing effective target-selection algorithms will require understanding the correlations of clutter and target returns from the various sensors, either at decision or feature level.

The ideal experiment is to collect the maximum amount of data, representing the full spectrum of features available for each sensor under consideration. The necessary spatially coregistered data sets will be difficult to achieve. Doing so will require the special research-grade instruments described in previous sections. For example, radar data should be taken with widest frequency band possible, recorded for all polarization combinations, and processed for maximum spatial resolution. Similarly, for thermal IR, data should be taken at the highest sensitivity (i.e., lowest noise-equivalent difference temperature), at maximum spatial resolution, and preferably at high spectral resolution. High-resolution data can always be degraded by processing on any axis, if it is later deemed not of interest or not practicable.

The analysis would consist of determining correlations of target nominations arising from targets and clutter for each sensor. This could be done at the decision level, after processing for each sensor has been optimized, and performed at various thresholds. Correlations of target and clutter features from each sensor would also be determined. This experiment gives the best result that could be expected for a given sensor combination. It is useful to determine this optimum result, because it indicates if even the best attainable performance will be good enough. From this point, one can start to consider the cost of trade-offs that reduce performance of one or both sensors from the ideal.

As a starting point, a number of suboptimal instruments that have been built operate in field tests and collect data frequently. Any experiments conducted using these

instruments are necessarily constrained by previously made design choices in instrumentation, as well as by the accuracy of the navigation built into the platform. Nevertheless, there are a number of data sets that have been acquired that would be useful in assessing fusion prospects, at least at the decision level. Where the data has been available, some level of cursory analysis has been done, mostly concentrated on target correlations. It is likely that contractors have studied these correlations as well, but we have little insight into this process. The government should require rigorous analysis and reporting of this sort from future data collection or testing efforts.

One existing data set that could be exploited is from the VMMD tests at Aberdeen and Socorro. For these two sites, a variety of mines were emplaced both on and off road, and coregistered data sets were obtained by five contractors with multiple sensor suites. All suites contained GPR and active EMI sensors, and four of the five employed broadband thermal IR detection as well. At the least, this data set, if coregistered to sufficient accuracy, could support decision-level studies of correlations of false alarms and target returns. In addition, a recent BoomSAR data collection at Eglin AFB included a coregistered IR image.

Several others data sets will be acquired in the course of planned testing, including tests of the VMMD platforms and planned data collections in the forward-looking mine detection program. Before the tests take place, some consideration should be given to the features that should be recorded by each sensor to support more elaborate feature-level fusion schemes.

There are two sensor combinations of particular interest for which we are not aware of any plans for data collection. These are a forward-looking GPR combined with NQR and a combination of forward-looking and down-looking GPR. The first is of interest, given the recent progress in NQR research and its promise to provide high-confidence detection of explosives, which would markedly reduce false alarms. The second may provide some level of clutter reduction because in the two implementations the GPR sees very different competing clutter phenomenology. A first cut at fusion would require only an integration or coregistration effort of current sensor builds. More extensive studies should be undertaken using more flexible research instruments that better span parameter space, as described in Chapters III and IV.

RECOMMENDATIONS

1. Initially, analyze at the decision level currently available data to determine target and clutter decorrelations.

2. Make raw data from all sensors a deliverable for all future tests and data collections, including “operational” tests to determine P_d and FAR .
3. Require analysis and reporting from contractors. Initiate an independent analysis effort.
4. Spatial control and precise co-registration should be a central focus of all future data collections.
5. Construct research-grade instruments described in Chapters III and IV; task them to collect coregistered data with best available EMI, magnetometer, IR, NQR, and neutron activation analysis sensors. The design of this experiment, target and clutter environment, sensor selection, etc., should be the subject of intensive study.

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IX. UNEXPLODED ORDNANCE

Application of GPR for detecting UXO is sufficiently different from detecting mines that it deserves separate discussion. The differences span target characteristics, the environment in which targets are found, and the mission requirements. UXO targets are universally metallic, near-perfect conductors with large dielectric contrast to any soil. Thus, on the positive side, the mine-detection difficulties of finding dielectric targets with low dielectric contrast do not apply. For UXO, however, there is no analog to the "easy" mine problem in the low-clutter road environment. UXO is found in impact areas, safety zones, disposal pits, and a large variety of other areas, but not, except coincidentally, in roadways. In addition, the depth requirement for UXO will generally be much greater than for mines. Depths of penetration can be many meters for large ordnance items, although on some sites most UXO is found in the top 20 or 30 cm of soil. Required depths of clearance can range from surface only to depths exceeding 3 m. All of these differences change the outcome of the trade-off in resolution versus penetration depth.

As we did throughout the report, we considered what would be the appropriate niche for GPR in the UXO problem, seeking potential for a unique capability not afforded by any other current sensor. Among the UXO missions described in Chapter I, GPR is most likely to play a role as a wide-area search tool and may provide discrimination capability to screen cues from another sensor. The mission of production search on surface-based platforms to detect each individual UXO is not likely to involve GPR. There are other sensors that simply work better for detection. All the targets are metal, most are steel, and EMI and magnetometers are reasonably effective at finding ordnance, although not discriminating it from other metal debris. The penetration depth, especially for magnetometers, is much better than what would be expected for GPR in all but the most benign conditions.

A. AREA DELIMITATION

For area delimitation, identifying areas as clear or likely to be densely contaminated with UXO, large tracts of land require rapid evaluation, preferably from an airborne platform. Although it is yet to be proven, GPR may be effective in a mission to identify forgotten impact areas, bombing targets, or disposal pits. At such sites, one would expect

large quantities of surface and near-surface contamination that could be detected by a radar. Even for bombing ranges, a large fraction of UXO and scrap will be near and on the surface, so the inability of GPR to detect the deepest penetrating large bombs will not necessarily be a limiting factor. There is a limited list of other technologies applicable to this mission. Towing a magnetometer below a helicopter may be possible, but such an arrangement will have severe terrain constraints. If there is substantial surface contamination and the GPR requires a magnetometer to be effective, airborne X-band SAR, laser reflectance, or visible imagery should be evaluated as alternatives.

The radar signature of an impact area is not currently known. Further, the sensor requirements in terms of P_d and FAR on individual items needed to provide useful area delimitation have not been quantified. In general, for identifying groups of items, there is no need to detect every ordnance item. However, there is a need for a sufficiently low FAR that uncontaminated areas can be identified as such.

Experimentation to explore GPR for the airborne UXO detection mission is limited, and there is a need to establish a ground-truthed baseline for GPR in the mission of detecting large concentrations of UXO, such as in impact areas or disposal pits. Several systems were tested at Jefferson Proving Ground, but this test was intended only to score current capability against individual ordnance items, not to evaluate the ability to detect concentrations of items or to provide data for system development. The Environmental Security Technology Certification Program (ESTCP) and Army Corps of Engineers funded SRI to fly a UHF UWB radar at Buckley Field in the summer of 1999, but based on these results did not support follow-on testing at Badlands Bombing Range. The most rigorous experiments to date are the BoomSAR measurements of fields seeded with UXO targets. In combination with previous Yuma measurements, these measurements yielded a large quantity of UXO signatures of individual items; however, there is a need for attention to processing for the UXO problem. There are few published results to date on UXO. A great deal of progress has been made understanding the BoomSAR mine signatures from the Yuma data, with the aid of detailed computer modeling done at Duke. There is a beginning effort to do calculations for UXO feature identification.

B. DISCRIMINATION

Another possible role for GPR in UXO detection is discrimination of target nominations cued by another sensor using either imaging or resonance and polarization, as discussed in Chapter VI. There is ongoing work evaluating the use of complex natural

resonance to estimate length and depolarization to estimate aspect ratio. Some experimental success has been reported in a highly controlled environment at Tyndall AFB. For imaging there is little evidence to date of an ability to distinguish targets from clutter. For broad applicability, there is a requirement to overcome the physics problem of a need for high frequencies for resolution, but the accompanying inability of high frequencies to penetrate the ground. However, research into this application is immature.

C. RECOMMENDATIONS

1. Establish a baseline capability for airborne GPR detecting high-density targets such as impact areas or disposal pits. The DARPA UHF SAR could be tasked to determine this baseline and to collect data to support further research for algorithm development and system definition.
2. Embark on a scientific study of airborne GPR for area delimitation. First, determine the target types, depth profiles, densities, and so forth, for these sites. Second, determine characteristic signatures and the radar parameters necessary to exploit them. Third, determine the requirements for group detection.

X. CONCLUSIONS AND RECOMMENDATIONS

Here we summarize the major conclusions and recommendations of this study. We discuss in detail recommendations for a large-scale research program, as well as some modifications that could be made in current programs to maximize the collection and analysis of data of opportunity. In addition, throughout the report are scattered specific questions of interest and recommendations for program-specific research efforts. These are summarized in Table X-2. Recommendations have been formulated in the context of our contention that effort should be focused on missions where GPR brings a unique capability to bear, while recognizing that the eventual role of radar will depend on its success and on the success of competing sensors under development. Some competing sensors (e.g., NQR) look very promising, but are early in their development. Thus, their eventual impact is difficult to judge at this time. For that reason, focused research on GPR should continue, as there are cases where GPR may offer our best or, perhaps, only viable sensor option. The important thing is to focus research assets on those areas that represent roadblocks to adequate GPR performance. The recommendations provide our view of those roadblocks and possible approaches toward removing them.

A. CONCLUSIONS

1. Despite significant investment over a long period on GPR, the various suites of sensors developed have not yet met operational requirements. Although we recognize the legitimate pressure to field operational systems, that pressure can be counterproductive when the phenomenology controlling performance is not sufficiently well understood. We believe that advanced development work must be preceded by concomitant research understanding. Currently, the preponderance of data being analyzed has come out of system development efforts and has been collected with equipment designed to be operational or near-operational, or with instruments of opportunity. As a result, high-quality research data on which to base system trade studies, develop radar specifications, or explore advanced algorithms is scarce.
2. Too little analysis has been carried out on the data that has been obtained. Even though existing measurement systems may not be ideal, field demonstrations and operational tests produce large quantities of data, and valuable understanding can often be gleaned from data collected. It appears that in many cases programs are constrained such that only analysis efforts directly

applicable to the test at hand are undertaken. Most data has been analyzed only by the system contractor to meet the contract requirements of a specific program. A synergistic analysis effort that stretches across programs might provide real dividends.

3. While there are exceptions, current system performance is typically limited by false alarms. That is, detection is clutter limited, not noise limited. Because the inherent detectability (i.e., detectability in a noise background) of most targets has been established, the question becomes how target returns differ from clutter returns. Increasing computer power in shrinking packages promises the operational application of sophisticated signal-processing techniques for separating targets and clutter. Those techniques require the definition of feature spaces in which targets and clutter show separation. Only when target and clutter characteristics are both well understood can signal processing be applied effectively.
4. Much more effort has been spent studying target characteristics than has been spent on clutter. This is not surprising. There is a limited set of distinct targets, and although the target geometry and composition can be complex, they are well defined. Efforts defining target signatures are necessary, and target-related research should continue. Substantial efforts, however, must be focused on clutter research and data collection.
5. The capabilities of EM models to describe counter-mine scenes of interest have grown enormously over the past few years. The sophistication of models is now such that credible synthetic data can be created. This ability should make modeling a key player in system design, algorithm development, and performance prediction. The modeler, however, must understand what parameters to incorporate in the model. Predicting performance requires understanding sensitivities to the environment. As noted above, targets are well understood and therefore can be well modeled, but we currently lack the understanding of clutter that would allow it to be accurately modeled. Only when that understanding is gained will models provide data useful in algorithm development.
6. Incorporation of diverse expertise in sensor hardware, algorithm development, modeling, and testing has been beneficial. The direct involvement of university-based research in the counter-mine problem through the MURI has provided significant insights, particularly in the broad spectrum of approaches that have been applied to the modeling and signal-processing areas. Similarly, the red team approach to the HSTAMIDS program, which is developing a handheld mine detector incorporating GPR and EMI sensors, has resulted in better understanding of the sensor functionality and performance improvements.

7. There is a need for controlled, repeatable testing to evaluate sensor performance independent of operator skill and technique and not subject to uncontrollable alterations in the environment. This capability is important for comparing different sensors and tracking changes in performance with sensor modifications.

B. RECOMMENDATIONS

1. Research should be focused on forward-looking standoff detection, initially exploring detection of antitank mines in roads.
2. At present, for the GPR problem no framework for the classification of clutter exists that is comparable to the clutter taxonomies used in other radar applications. Thus, the focus of research should be on defining, understanding, and measuring clutter. To that end, the following steps should be undertaken:
 - Determine the range of clutter and target data needed to support system design decisions, algorithm development, and modeling research. Considerations should include definitions of instrument parameters, targets, and backgrounds and their relation to the needs of current and planned programs.
 - Build a suite of research-quality data-collection instruments not constrained by operational requirements.
 - Collect and analyze clutter and target data, with a focus on clutter. Data collection should be driven by three concerns: better understanding clutter characteristics, providing training and test data for signal-processing algorithm development, and providing both input and validation data for EM model development.
 - Table X-1 provides our recommendations for the system design and parameter space to be covered by the instruments and the data collection. These recommendations are for reasonable, notional parameters for the instruments and the experiments, but they do not represent the results of a rigorous study of the trade space or practical engineering considerations. As such, final designs should be based on an extensive red team effort involving hardware engineers, signal processors, modelers, and test designers.
 - Develop a research program to provide the necessary knowledge of clutter characteristics. Such a program should involve a careful physical and EM description of environments of interest, ranked in order of importance. These could be used to prioritize data collections. Clutter is highly variable, and that complicates its description. The focus of the research

Table X-1. Data Collection Matrix

Parameter	Forward Looking	Down Looking
Frequency Range	200 MHz—4 GHz	200 MHz—6 GHz
Polarization	Full	Full
Grazing Angle	10–50 deg at 10-deg intervals	Full hemisphere
Aspect Angle	~0–180 deg at 10-deg intervals, as appropriate	Full hemisphere
Road/Terrain/Area	Unpaved dirt Macadam—various constructions Asphalt Flat terrain—bare and vegetated Hectare(s) for each	Increasingly complex media, small patches
Target type/configuration/quantity	Standard metal and dielectric targets AT mines Scatterable mines Submunitions Clutter 10's of each target type in each terrain, surface and buried, as applicable	Individual target interrogation: buried mines UXO Discrete clutter objects Standard metal and dielectric targets
Spatial resolution	< minimum target size, best attainable with radar, centimeters	< minimum target size, best attainable with radar, centimeters
Waveform	Stepped frequency	Stepped frequency
Azimuthal Processing	SAR (cross-track)	3-D SAR
Antenna Height	3 m–6 m	Close coupled to earth
Standoff Range	3–20 m	0

should be an attempt to group clutter into a limited number of classes relevant to system design. To that end, a careful evaluation of a combination of statistical and discrete approaches for clutter characterization is warranted.

- Support research on the characterization of EM propagation and scattering in soils. Investigate a statistical paradigm similar to the atmospheric weak-scattering case. Bolster theoretical analysis with carefully calibrated measurements and computer modeling. Efforts should begin on simple, well-characterized media. As understanding is gained, more complex compositions should be tackled.
3. We should do a better job of exploiting data from current programs. There are two important facets of such an effort:

- Make data and specific analyses deliverable from contractors. Every effort should be made to ensure that data collections and analyses serve the broader goals of the countermine and/or UXO detection program.
 - Set aside resources for independent analysis of data. Such efforts provide potentially valuable insights that are not likely to come out of program-driven analyses. An example is the red team analysis of HSTAMIDS data, which provided significant input to focus system improvements.
4. The HSTAMIDS red team is an example of how accessing a larger body of knowledge in the countermine area can pay dividends for a specific program. Research results coming out of the MURI and applied to data from the BoomSAR, Wichmann, and GeoCenters systems show significant performance improvements. Such interactions should be encouraged through a red team approach to system engineering decisions.
 5. As discrimination of mines from clutter is typically the problem faced by mine detection systems, discrimination algorithm development is the key to performance improvement. Algorithm success depends on the signals provided. Thus, measurement, modeling, and detection/discrimination algorithm development must be tightly integrated.
 6. Sensors delivered to the government at the end of programs should be well documented and well calibrated.
 7. Existing platforms from other DoD programs should be leveraged to the extent possible. Specifically, the Defense Advanced Research Projects Agency Ultra-High Frequency Ultra-Wide Band SAR (DARPA UHF UWB SAR) and the CECOM tactical unmanned aerial vehicle (TUAV) SAR should be tasked for data collection and baseline performance determination for countermine and UXO detection.
 8. Develop protocols and equipment for standardized sensor testing.
 9. Other specific recommendations are summarized in Table X-2.

Table X-2. Other Recommendations

Soil Characterization	<ul style="list-style-type: none">• Develop a statistical description of soils, patterned on atmospheric physics• Develop numerical modeling approaches that accurately represent realistic soils• Initiate a measurement program to support above
Discrimination	<ul style="list-style-type: none">• Continue modeling efforts to identify discriminants• Use above data collection for signal processing• Investigate utility of polarization• Investigate utility of spectral response• Curtail complex natural resonance research• Curtail 3rd harmonic research
Fusion	<ul style="list-style-type: none">• Require analysis and reporting of target and clutter statistics for current data• Make raw and processed data deliverable. Initiate independent analysis• Task collection of coregistered data sets for<ul style="list-style-type: none">• Forward-looking radar with NQR• Forward-looking and down-looking radar
UXO	<ul style="list-style-type: none">• Establish a baseline for detection of high density impact areas from an airborne platform• Study statistical requirements for airborne area delimitation• Study system engineering requirements for airborne radar

APPENDIX A

RADAR TERMINOLOGY

APPENDIX A

RADAR TERMINOLOGY

A. IMAGES

Radar engineers generally speak of "images" in terms of the results of processing specific waveform and data collection geometry combinations. As the nomenclature does not necessarily match what the rest of the world envisions when it hears the word "image," it is likely worthwhile at this point to provide some clarification.

Radars are capable of resolution in range, angle, and Doppler space. Here we are only concerned with range and angle because both the targets of interest and clutter are not moving. Radar images are generally defined in terms of the dimensions for which steps have been taken to improve resolution over that available from a simple radar.

The least complicated radar image is one obtained by providing and processing a high-bandwidth waveform, where no attempt is made to improve angular resolution over that provided by the beamwidth of the antenna. This is often spoken of as a one-dimensional or high-range resolution (HRR) image. The resulting processed output is often plotted as a simple amplitude as a function of time or range. Sequences of HRR images can be stacked in a waterfall plot to provide the appearance of a two-dimensional image, but such a presentation is not what is generally meant by the term.

Motion of the radar antenna in one or both of the cross-range directions can be used to provide what is known as a synthetic aperture; that is, an effective aperture produced by appropriately combining the returns gathered by the real antenna at a number of locations in cross-range. If the motion is along one cross-range dimension, data in angle space can be transformed to data in the corresponding cross-range space, where the resolution in cross-range depends on the frequency and the angle subtended. The resulting output is a two-dimensional or SAR image, with improved resolution in range and one cross-range dimension. Return from scatterers along the other cross-range dimension are collapsed in processing to the appropriate range and cross-range pixel. Such images are generally in a pixel format, with each pixel color or gray shade coded for its radar cross section (RCS).

Motion in the second angular dimension can be similarly processed to provide what is commonly called a three-dimensional SAR image. The elements are then normally thought of as voxels, with a defined resolution in each of the three orthogonal directions.

B. OTHER TERMS

1. k-space

Uniform plane waves play a considerable role in electromagnetic theory and particularly in the theory of radar imaging (SAR, ISAR, microwave holography, microwave tomography, etc.). The propagation of a uniform plane wave in a homogeneous medium is completely characterized by its spatial frequency, \mathbf{k} , which may be represented as a vector of magnitude $|k| = 2\pi/\lambda$, with projections on the x, y, and z directions ($\mathbf{k} = k_x\mathbf{u}_x + k_y\mathbf{u}_y + k_z\mathbf{u}_z$). Thus the space of all possible plane wave frequencies and propagation directions can be mapped directly into a three-dimensional space denoted "k-space." It is convenient to characterize the illumination spectrum of a point to be focused in an imaging radar system by its spectral support in k-space. The spatial impulse response corresponding to this illumination function is obtained by a discrete Fourier transform (DFT).

2. Radar Bands

Several conventions have arisen to designate the bands used by radar and other electromagnetic systems. Although "official" commissions have attempted to dictate otherwise, the radar community has settled on the following notation, which is (almost) universally understood.

Band Designation	Frequency Range
VHF	30–300 MHz
UHF	300–1000 MHz
L	1–2 GHz
S	2–4 GHz
C	4–8 GHz
X	8–12 GHz
Ku	12–18 GHz
K	18–26.5 GHz
Ka	26.5–40 GHz
Millimeter	> 40 GHz

It is becoming common to use the following designations for bands above 40 GHz, but this usage is not yet universal:

V	40–70 GHz
W	70–110 GHz

APPENDIX B

PRESENTATIONS TO THE JUXOCO GPR WORKSHOP

APPENDIX B

PRESENTATIONS TO THE JUXOCO GPR WORKSHOP

Azevedo, Steve (Lawrence Livermore National Laboratory), *Land Mine Detection Using Micropower Impulse Radar*

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Carin, Larry (Duke University), *Duke MURI work*

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Dean, Arnold (GeoCenters), *Vehicle and Unit Area Radars*

Fialar, Phil (Mirage), *Circle SAR*

Gader, Paul (University of Missouri, Columbia), *The Roles of Clutter and Signature Libraries in GPR Algorithm Development*

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Koh, Gary (CRREL), *Radar Detection of Non-metallic Simulant Land Mines*

Kositsky, Joel (SRI), *GPR at SRI: Airborne GPR, Forward Looking GPR System, Harmonic Radar*

Lang, Dave (Marconi, formerly GDE), *Hand Held and Vehicle Mounted Mine Detection Systems*

Rappaport, Carey, and Miller, Eric, (Northeastern University), *NEU Humanitarian Demining MURI Efforts on Clutter Modeling and Inverse Scattering Methods for GPR*

Scott, Waymond, (Georgia Institute of Technology), *Research on Subsurface Detection at Georgia Tech*

Sichina, Jeff (Army Research Lab), *Boom SAR*

Stolarczyk, Larry (Raton), *Electromagnetic Wave Detection and Imaging Transceivers (EDIT) for Shallow and Deeply Buried Objects*

Witten, Tom (NVESD For Planning Systems), *High Resolution GPR*

APPENDIX C

JUXOCO GPR WORKSHOP PANEL MEMBERS

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APPENDIX D

LIST OF ACRONYMS

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AFB	Air Force Base
AP	antipersonnel
ARL	Army Research Laboratory
ARO	Army Research Office
ASTAMIDS	airborne standoff mine detection system
AT	antitank
ATD	advanced technology demonstration
ATR	automatic target recognition
BOR	body of revolution
BRAC	base realignment and closure
CECOM	Communications Electronic Command
CRC	Coleman Research Corporation
CRREL	Cold Regions Research and Engineering Laboratory (U.S. Army Corps of Engineers)
CW	continuous wave
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DOE	Department of Energy
DOT-FHWA	Department of Transportation-Federal Highway Administration
DSWA	Defense Special Weapons Agency
EDIT	Electromagnetic Wave Detection and Imaging Transceiver
EFIE	electric field integral equations
EM	electromagnetic
EMI	electromagnetic induction
ESTCP	Environmental Security Technology Certification Program
FAR	false-alarm rate

FDTD	finite difference time domain
FFRDC	Federally Funded Research and Development Center
FL	forward looking
FM	frequency modulation
FMCW	frequency modulated continuous wave
FMM	fast multipole method
FOLPEN	foliage penetration
FUDS	formerly used defense site
GPR	ground-penetrating radar
GPS	Global Positioning System
GSTAMIDS	ground standoff mine detection system
HRR	high-range resolution
HSI	hyperspectral imaging
HSTAMIDS	handheld standoff mine detection system
IDA	Institute for Defense Analyses
IR	infrared
JUXOCO	Joint Unexploded Ordnance Coordination Office
LLNL	Lawrence Livermore National Laboratory
MIR	micropower impulse radar
MoM	method of moments
MURI	Multi-University Research Initiative
NEU	Northeastern University
NQR	nuclear quadrupole resonance
NVESD	Night Vision Electronic Sensors Directorate
ORD	operational requirements document
OSU/ESL	Ohio State University ElectroScience Laboratory
P_d	probability of detection
P_{fa}	probability of false alarm
PSM	polarization scattering matrix
R&D	research and development
RCS	radar cross section

RF	radio frequency
RFI	radio-frequency interference
RMPA	resonant microstrip patch antenna
SAR	synthetic aperture radar
TEMR	transverse electromagnetic rhombus
TNA	thermal neutron activation
TUAV	tactical unmanned aerial vehicle
UHF	ultrahigh frequency
UWB	ultra-wideband
UXO	unexploded ordnance
VMMD	vehicle-mounted mine detection

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13. ABSTRACT (Maximum 180 words) <p>This report documents the results of an IDA assessment of the state of research on ground-penetrating radar (GPR) as applied to countermine and unexploded ordnance clearance. This report examines existing GPR research and development efforts with emphasis on missions where GPR has the potential to provide a unique capability and to achieve operationally meaningful performance. We identify data collections and analyses that will be necessary both to make decisions about the suitability of GPR for particular missions and to achieve performance gains necessary for operational utility. The potential capabilities of ground-penetrating radar could, if realized, make it a useful tool for the detection of mines and UXO. These potential capabilities, however, have not been demonstrated in practice. In most cases, performance is limited by clutter, not by insufficient target signal for detection in noise. Thus, discrimination of targets from clutter is the fundamental problem to be solved to improve GPR target detection performance. Among the numerous research efforts that must be undertaken to advance GPR in any application are soil characterization, discrimination, and modeling. Since it is likely that radar will be paired with another sensor for any application, research to support sensor fusion is important.</p>				
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