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**GROUND-PENETRATING RADAR (PAPER I)***Lawrence Carin, Duke University*

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This appendix focuses on the application of ground-penetrating radar (GPR) to landmine detection. We address the particular application for which the sensor is near the ground.<sup>1</sup>

**BASIC PRINCIPLES AND MINE FEATURES**

GPR senses electrical inhomogeneities, with these manifested, for example, by the electrical contrast of a metal mine in the presence of a far-less-conducting soil background. Of much more difficulty, GPR senses the electrical inhomogeneity caused by a dielectric (plastic) landmine in the presence of soil. Often this contrast is very weak, implying that the landmine GPR signal is very small. This is exacerbated by the fact that there are many electrical contrasts that may exist in the landmine problem, which significantly complicate sensing. For example, the largest contrast typically exists between the air and the soil, and therefore GPR is typically characterized by a very large “ground bounce.” If a landmine is buried at a shallow depth, such that the available bandwidth implies limited resolution, the often weak landmine signature will be “buried” in the very strong ground-bounce return. This implies that bandwidth (resolution) plays an important role in defining the target depths at which a landmine may be observed by GPR. We also note that natural subsurface inhomogeneities, such as rocks, roots, surface roughness, and soil heterogeneity (e.g., pockets of wet soil), also yield a signature

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<sup>1</sup>I do not consider the use of radar for airborne, wide-area sensing because it was indicated to be of less interest to RAND and the Office of Science and Technology Policy.

to a GPR sensor; such clutter represents the principal source of false alarms.

### **CURRENT STATE OF DEVELOPMENT**

GPR is one of the oldest landmine technologies, probably second only to induction sensors. Nevertheless, development is still at a relatively early stage, as only very recently have electromagnetic models been developed to aid in phenomenological understanding. Consequently, only recently has enhanced understanding of the underlying phenomenology been exploited in new systems, such that the ultimate potential of GPR can be realized.

As for recent efforts, GPR is being employed by Cyterra in the context of the U.S. Army Handheld Standoff Mine Detection System program. The Cyterra system is based on multiple spiral antennas and operates in the frequency domain. Another important system has been developed in Germany by Gunter Wichmann, with this technology now being pursued in the United States by NIITEK. The so-called Wichmann system operates in the time domain, with a very large bandwidth (from approximately 200 MHz up to 10 GHz). A novel antenna design has significantly reduced the antenna “self clutter,” resulting in a very-high-resolution transient waveform. This system is not at the stage of development of the Cyterra system, but it represents a significant enhancement in GPR technology (the result of three decades of development in Germany).

With regard to development of modeling tools to understand GPR phenomenology, there are several universities that have directed significant attention on GPR for landmine detection, including Duke, Georgia Tech, Northeastern, and Ohio State. The state of model development is now becoming quite sophisticated; it is now possible to rigorously model a three-dimensional GPR system on a computer.

### **CURRENT CAPABILITIES AND OPERATING CHARACTERISTICS**

It is difficult to separate GPR performance from the particular system and classification algorithms in question. Moreover, the Cyterra system combines both GPR and induction, and therefore the perfor-

mance of this system is generally not simply based on the GPR characteristics.

It can be said, however, that significant strides have been made in the last several years in the context of GPR sensors. There is a “blind grid” of buried landmines and clutter developed by the Joint Unexploded Ordnance Coordination Office at Fort A. P. Hill, Va. The investigator is told where to sense (on the grid), but the subsurface target identity is unknown. Using the Wichmann system, with very preliminary algorithm development, approximate results are a probability of detection of 0.8 at a probability of false alarm of 0.1. It is anticipated that these results will improve as the algorithms are enhanced. It is believed that the Cyterra system achieved comparable results when it deployed its GPR alone (although the results were far better when the Cyterra GPR and induction sensors were fused). This test site was designed to be particularly challenging.

It is important to emphasize that the quality of the signal-processing algorithms plays a very important role in the ultimate effectiveness of a GPR system. For example, GPR has been used in the context of the Ground Standoff Mine Detection System (GSTAMIDS) program (vehicle program). Previously, GPR produced an unacceptably high number of false alarms for on-road sensing. The recent development of such algorithms as hidden Markov models has significantly aided GPR classification performance within the GSTAMIDS program, and these algorithms (and performance) continue to improve.

#### **KNOWN OR SUSPECTED LIMITATIONS ON APPLICABILITY**

As indicated in the first section, GPR is not a landmine sensor—it is an electrical (and possibly magnetic) contrast sensor. Any such contrast will register a signal to GPR, and often subsurface clutter can manifest a signal comparable to that of a landmine. Moreover, in the context of plastic or dielectric (wood) mines, the properties of the soil play an integral role in ultimate GPR utility. For the same mine, a given GPR can be effective or ineffective depending on the soil properties. This implies that such elements as rain, or the lack of rain, can play a critical role in the context of the target-soil contrast, affecting ultimate sensor performance.

There are also important issues in the context of very small plastic mines buried at shallow depths (e.g., flush-buried). The strong ground-bounce return can “mask” the much smaller signal from the landmine. This is why bandwidth is a particularly important issue: A higher-bandwidth GPR system will have enhanced resolution to deal with shallow-buried targets.

### **ESTIMATED POTENTIAL FOR IMPROVEMENT (OVER TWO TO SEVEN YEARS)**

GPR has limitations, as indicated in the previous section. However, it is likely to be an integral component of any landmine sensor suite because a properly designed system, with appropriate signal-processing algorithms, has demonstrated significant potential in quickly sensing landmines. In concert with other sensors, such as induction and nuclear quadrupole resonance (NQR), GPR constitutes a very powerful technology.

There is significant potential for GPR improvement in the next two to seven years. As indicated in the Current State of Development above, only recently has the fidelity of electromagnetic models put developers in a position where they can *understand* the various tradeoffs in GPR design, such as antenna configuration, bandwidth, and polarization. Now that this insight can be transitioned to the development of improved GPR sensors, there is significant potential to realize significant improvements in GPR performance, particularly in the context of a multisensor suite.

Issues that should be addressed include examination of the effects of antenna design on ultimate performance. The Cyterra and Wichmann systems, for example, are based on entirely different antenna systems, although both are yielding promising results. It is of interest to carefully examine the relative strengths and weaknesses of each system (and others) such that an overall improved design can be realized. Moreover, within the context of a multisensor suite, one should examine design of the GPR such that it is most effective, for example, as a prescreener for such sensors as NQR (which appears to be a promising confirmation sensor).

## **OUTLINE OF A SENSIBLE RESEARCH AND DEVELOPMENT PROGRAM**

The ultimate multisensor platform is almost surely going to include GPR as an integral component. I would therefore recommend first performing a systems-level study to identify the role of GPR and how it will be manifested in the context of multiple sensors (e.g., GPR and induction may be prescreeners for NQR). Once these systems-level issues are addressed, it is desirable to design a GPR system that would meet the objectives of the overarching systems-level mission. The ultimate system construct may constrain or motivate such items as GPR bandwidth, polarization, antenna design, and size.

In addition, there are several existing systems (e.g., the Cyterra and Wichmann systems) that operate in very different ways, although each has yielded encouraging results. It is of significant interest to gain a further understanding of these systems, based on measurements and modeling, such that one may take this insight to develop the next-generation GPR system. This research should build on and extend recent encouraging research in the area of modeling and radar development.

It should also be emphasized that, as indicated above, within the context of GPR, one cannot separate the system from the associated signal processing and ultimately how the system will be deployed by the user. It is strongly recommended that the modeling, sensor design, and GPR signal processing be strongly coordinated from the outset. Typically, GPR systems are designed prior to considering how the data will be processed, and therefore processors must deal with the subsequent GPR data without the ability to motivate change in underlying sensor design. GPR must be viewed in the context of an overarching system, accounting for the other sensors that will be deployed as well as the ultimate manner in which the data will be processed and presented to the user.

## **REFERENCES**

The best source of reference to field-testing papers is likely to come from reports delivered to the sponsors (Counterintelligence Office, Fort

Belvoir, Va.) and from the proceedings of the International Society for Optical Engineering's AeroSense Conference (primarily from 1998 to 2002).