
X-RAY BACKSCATTER (PAPER I)

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OVERVIEW

Most of the concepts presented in this paper feature AS&E's patented backscatter technology, which uses a scanning pencil beam of x rays. Backscatter technology should be most applicable as a tool for identifying antipersonnel mines that are planted no more than 3 inches below the surface or that are lying on the surface but are hidden by camouflage or vegetation. Many groups have researched standard x-ray backscatter over the past years as a potential mine detection tool. That success has been limited at best. We present here concepts that, as far as we know, have not been implemented, although our experience with similar systems indicates that it would be relatively straightforward to do so. We present these ideas, all studied by Monte Carlo simulations and most of them patented, as new techniques that have the potential for eliminating some of the problems encountered in the past using x-ray systems for humanitarian demining.

¹American Science and Engineering Inc. (AS&E) is pleased to submit this appendix to RAND for use by its Mine Detection Technology Task Force. As a result of a request by RAND to Dr. Lee Grodzins, MIT Professor Emeritus, and Vice President, Advanced Development, AS&E, we have assembled a series of concepts that could be employed to detect a wide variety of landmines in a relatively short period and have the potential for being developed into deployable systems.

NATURE OF THE PROBLEM

According to reported estimates, approximately 100 million anti-personnel mines now lie hidden in the ground in 64 countries worldwide. These mines remain active for many years and kill or maim 25,000 civilians every year. The task of finding and removing these mines is monumental. Many of the mines that were close to or on the surface have become more deeply buried or are heavily overgrown with vegetation. In addition, many of the newer mines are clad with plastic, rather than metal, and the use of metal detectors to locate these mines is no longer effective. There is therefore an urgent need for new technologies to be developed that can effectively define an area containing antipersonnel mines, with minimal false alarms. Figure L.1 depicts the type of antipersonnel mine that drives both the mapping and detection requirements.

Although there has been significant effort aimed at the detection and clearing of various kinds of mines, what is needed is a methodology and system implementation focused on the safe and rapid delineation of boundaries of areas containing mines. This objective can be

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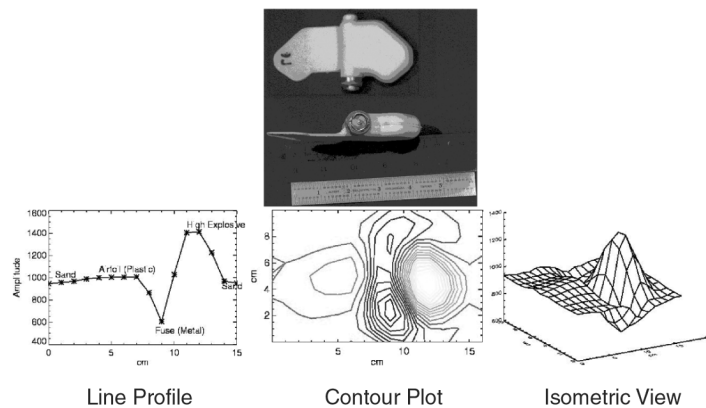


Figure L.1—High-Resolution Image of a “Butterfly” Antipersonnel Landmine

viewed from both a military/humanitarian and a commercial/industrial standpoint. In a military/humanitarian sense, governments seek to ensure that civilians relocating to areas where there have been conflicts will not be in danger of mutilation or death from contact with antipersonnel mines. Likewise, as commercial ventures begin to reclaim and reuse land as part of the Base Realignment and Closure process, there are usually areas of ordnance that need to be identified, mapped, and eventually cleared. The system that performs the detection and mapping operation must cover a large area—on the order of thousands of square feet—quickly, reliably, and safely.

AS&E'S POTENTIAL SOLUTION SET

The following paragraphs describe a number of potential approaches using x-ray backscatter to address the demining problem.

Background and General Remarks²

The signal of x rays scattered by a buried object is proportional to the product of a number of factors, which are as follows:

- The intensity of the x rays in the pencil beam emitted by the x-ray source.
- The attenuation of the x rays before the scatter.
- The probability of scattering in the back direction. (This probability depends inversely on the absorption power of the material to the incident and to the backscattered x rays. Organic materials typically absorb only a small fraction of the x rays, so that the scatter probability is high. Metals typically are strongly absorbing, and the scatter probability is low. Thus, organic materials are bright and metallic objects are dark in the image.)

²This appendix contains minimum background and detail. The background material for x-ray backscatter is well summarized in P. Horowitz, K. Case, et al., *New Technological Approaches to Humanitarian Demining*, McLean, Va.: MITRE, JSR-96-115, 1996.

- The attenuation of the x rays as they pass back out of the object and traverse the soil on the way to the detector.
- A factor that depends on the product of the density (ρ) and the thickness (t) of the object along the x-ray path. For thick objects, the dependence is weak. If the thickness is not known, then one is unable to get any measure of the density.
- The solid angle and efficiency of the backscatter detectors.

Single scattering dominates for objects on or just under the surface, but multiple scattering increasingly dominates as the sought-for object is more deeply buried. Explosive material, soil, and organics preferentially scatter, rather than absorb, the higher-energy x rays that are required to see objects below the surface. In practice, multiple scattering as well as single scattering must be considered to make an effective detector.

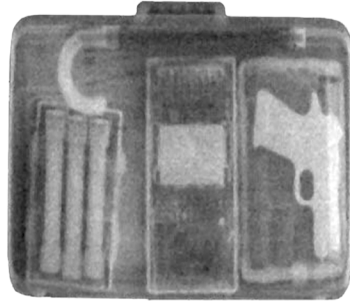
The most important information is the image itself. The operator must see a high-quality image to identify the objects being viewed. AS&E images typically have about 2-mm-diameter resolutions, adequate for even small landmines. At 1 ms per point, the area scan rate can be 3 sq ft per minute. The resolution in AS&E backscatter systems can be varied in situ. At a resolution of 4 mm \times 4 mm, probably adequate for many purposes, the scan rate can be more than a square meter per minute.

We note that all the devices described in this appendix can be mounted on a remote-controlled vehicle, with only the detectors suspended over the minefield by a boom. To produce an undistorted image the speed of the vehicle would need to be either regulated or accounted for, as AS&E does for its “X-Ray Van: Drive-By Backscatter Imaging” project.

Figure L.2 shows the ability of an AS&E backscatter image to clearly indicate the shapes of solid objects inside a suitcase despite a cluttered background. (We note that the monitor image is considerably crisper and more photographic-looking than the printed image in Figure L.2.)

To inspect terrain for antipersonnel mines, the system would be oriented facing the ground. The backscatter system might be applied

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NOTE: An example demonstrating the ability of backscattered x rays to distinguish solid objects against a cluttered background. Unlike transmission x-ray images, the backscatter image is formed without the need to place an imaging screen or other hardware on the far side of the subject.

Figure L.2—AS&E Backscatter Image

as the second stage of a two-stage process in which the first stage identifies suspect objects, and backscatter imaging verifies each threat. For example, the AS&E backscatter system could be integrated with the water-jet drilling system developed by the University of Missouri–Rolla as shown in Figure L.3. The water-jet system has been shown to have the potential for locating buried antipersonnel mines without detonating them, but it is unable to distinguish between mines and a variety of other solid objects. The use of backscatter imaging of all suspect objects could be a method to quickly dismiss false alarms and to help to identify the type of mines discovered prior to excavation.

The backscatter system in Figure L.3 employs a hollow spoked rotating wheel to create a scanning pencil beam of x rays. AS&E is developing a CRT (cathode-ray tube)–based approach to x-ray scanning to reduce weight and significantly improve flexibility. Figure L.4 shows that approach to x-ray beam generation combined with water-jet clearing of debris and topsoil.

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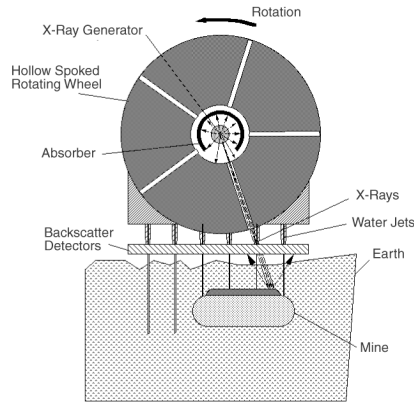
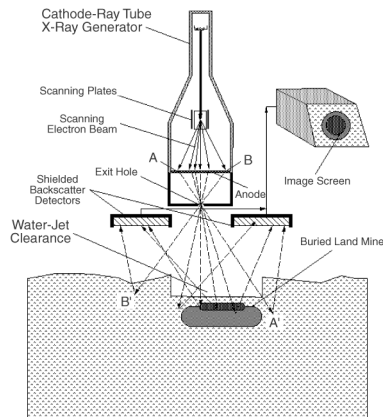


Figure L.3—Illustration of the Standard AS&E Backscatter System Adapted to Work in Conjunction with a Water-Jet Hole Drilling System

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NOTE: This system works in combination with a water-jet system to clear surface soil from above the suspect object to allow imaging at greater depths than are normally possible with backscattered x rays.

Figure L.4—Illustration of a Scanning Electron Beam Backscatter System

In some terrain, it may be practical to carry out airborne searches with the x-ray mine detection system suspended from a helicopter, but such a modality faces many problems not encountered with a ground-based system.

Shallow Angle Compton Scatter Detection

One method to increase ground penetration is shown in Figure L.5. The incident radiation enters the ground at a shallow angle, and the detectors are positioned to receive radiation that has scattered off the target at an angle in the 90° range. The energy of this scattered x ray is significantly greater than that of the 180° backscattered x ray, potentially allowing penetration depths greater than 5 cm.

Focused-Depth Compton Backscatter Imaging

The problem of imaging objects buried just below the surface is complicated by the irregular distribution of material (uneven terrain, rocks, debris, surface vegetation, etc.) on the surface. These features, collectively known as “surface clutter,” contribute strongly to the background counts and reduce the signal-to-noise ratio of the landmine image. AS&E has pioneered collimation methods to reduce the

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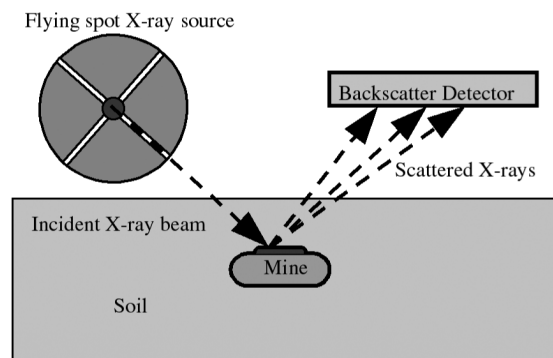


Figure L.5—Backscatter System Modified to Use Forward Scatter Radiation

signal from near-field clutter by adding collimation vanes in front of the backscatter detectors, as shown in Figure L.6. These vanes block photons emanating from depths other than the depth of interest. The collection efficiency of this geometry as a function of depth is shown in Figure L.7. Our experiments show that the signal intensity changes by a factor of two over a distance of just 1.2 cm.

Effective Atomic Number and Density Measurement with Compton Backscatter Imaging

Backscatter imaging is an effective modality to distinguish mines from false positive alarms (e.g., rocks, scrap metal, roots) by measuring the effective atomic number of the detected objects. The intensity of single backscattering with incident energies above about 100 keV is quite sensitive to large differences in the atomic number of the scatterer, such as plastic and steel. Single backscatter is, therefore, quite capable of distinguishing a chunk of metal from a plastic mine. However, to distinguish a plastic mine, with its effective Z of about 7, from rocks, with an effective Z of about 14, requires that one use

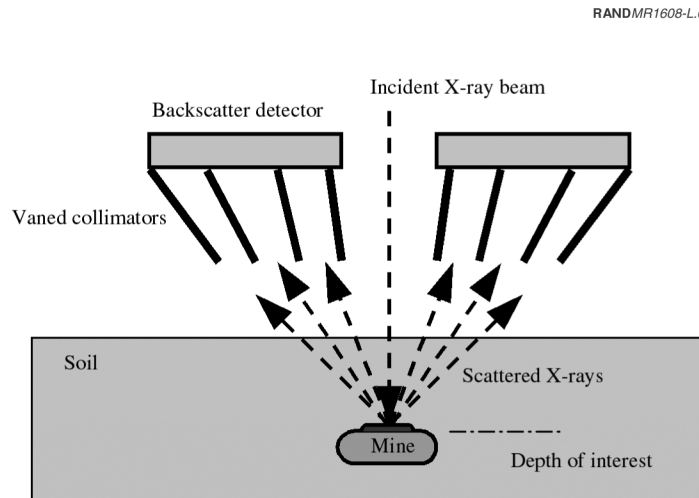


Figure L.6—Schematic Diagram of Vaned Collimator Imaging Technique

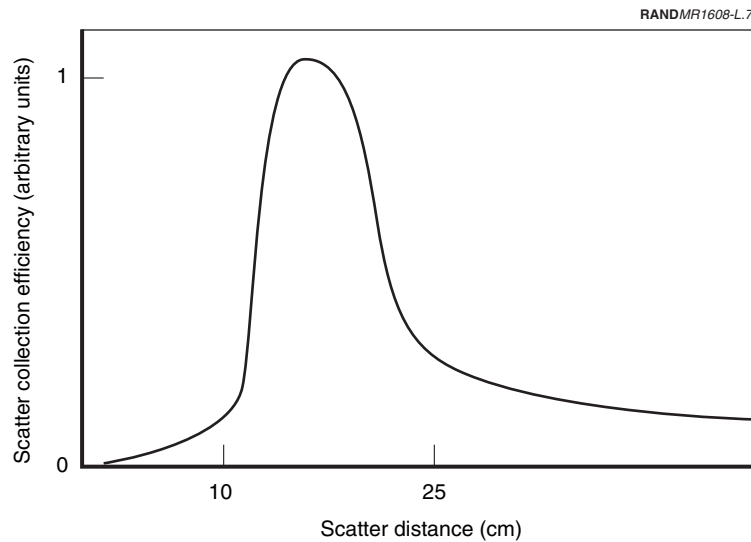


Figure L.7—Collection Efficiency as a Function of Depth in Inspection Tunnel Using Vaned Collimators

much lower x-ray energies (hence much reduced penetration) or a more sensitive backscatter technique. Calculations show that backscatter radiation intensity resulting from multiple scattering in the object is more sensitive than single scattering to the atomic number of the object.

Figure L.8 shows collimators that block photons that have a direct line of flight from the point of interaction in the target to the detector, while passing photons that have moved some lateral distance in the target before leaving the target. Other groups have used this method, first developed in the 1970s by F. Roder.

AS&E's method would extend the one-detector technique of others to the use of several independent concentric rings of detectors. Computer simulations indicate that the ratio of responses in the detectors gives a measure of the object's density, while the sum of signals in the set of detectors gives a measure of the effective atomic number.

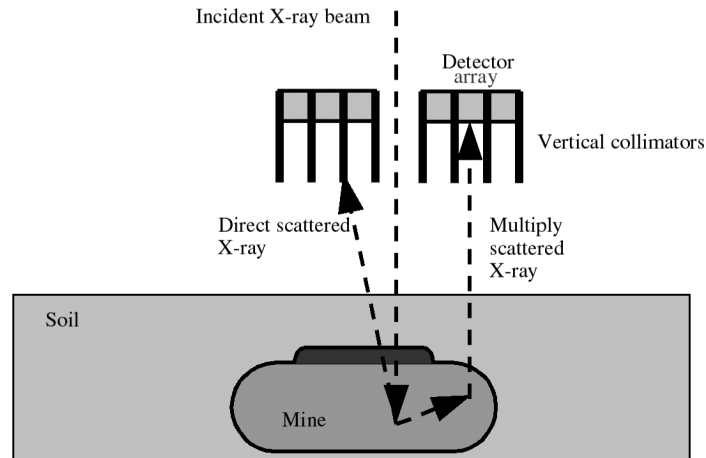


Figure L.8—Schematic Diagram of Backscatter Detector and Collimator Configuration to Measure Atomic Number

Backscatter System Configured for Optimum Density and Effective Atomic Number Measurements

Effective atomic number alone is often not an adequate metric to identify landmines because nonmetallic mines have a similar effective atomic number to that of organic material. The addition of density information can considerably improve our ability to separate either metal or plastic mines from a background including not only metallic objects and rocks (silicates) but also roots and other organic debris.

Figure L.9 is a schematic of a detector system that measures both the effective atomic number and the density. The inner set of detectors counts multiply scattered x rays, providing atomic number information. The outer set of detectors are collimated to restrict the thickness of the measuring volume and hence obtain density information. It is important to emphasize that, because the position of the x-ray beam relative to the ground is the same for all detected counts, one can

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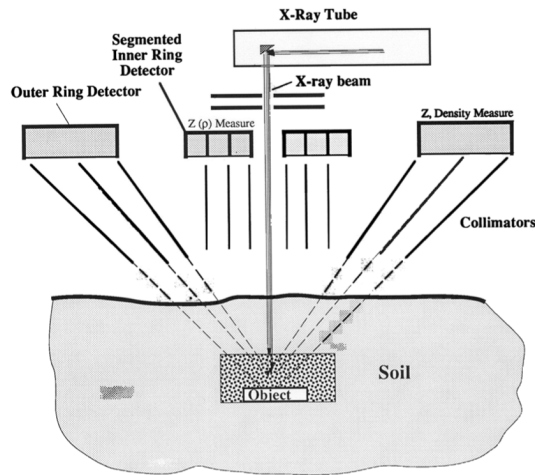


Figure L.9—Schematic Diagram of Backscatter Detector and Collimator Configuration to Simultaneously Measure Atomic Number and Density

sum the detector counts to produce a crisp image. If sufficient counts are available in individual detectors, then the images of each can give additional information. AS&E has carried out extensive and effective measurements of density distributions in luggage with the collimated detectors at right angles to the x-ray beam (AS&E's patented Side-Scatter Tomography). A right-angle measurement is not practical for landmine detectors, so the collimation cannot be as effective as it is for luggage. However, a depth interval can be defined well enough so that in many situations the deduced density can discriminate explosive material with densities in the 1.4–1.7 g per cubic centimeter range from such materials as roots that have densities less than 1 g per cubic centimeter.

Underground Source Transmission Imaging

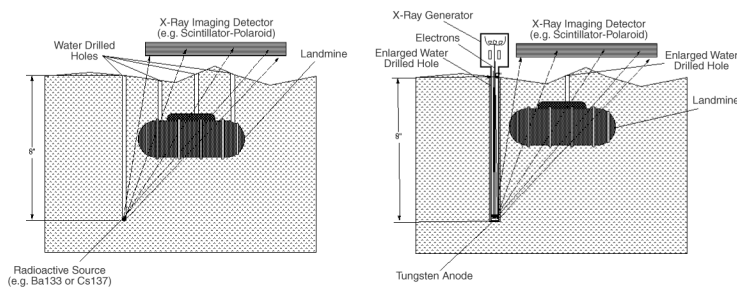
All the systems described above use backscatter imaging in part because the problem of imaging objects in the ground is perceived to

be a necessarily one-sided imaging task. A two-sided imaging solution, such as transmission x rays, can be made possible if one can place a source of intense radiation in a hole drilled to some distance below the surface. Figure L.10 outlines this concept.

The hole is drilled in a safe area adjacent to the area to be investigated. A transmission x-ray source or an x-ray generator is inserted in the hole so that radiation is transmitted through the earth and any buried objects are imaged at a detector similar to the digital-imaging detectors used for medical applications. For shallow mines, nearly the entire area below the detectors can be inspected. For deeper mines, a smaller area of ground will be within the volume that is penetrated by x rays. If mines are detected, their positions are noted and then used to direct demining work. Once the area is determined to be safe, the equipment is broken down and a new hole or holes can be drilled in the area that has been demined to reach farther into the minefield.

A small system using holes on the order of 20 cm deep could be used to identify potentially dangerous objects located by other mine detecting methods such as water-jet drilling and acoustic sounding.

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Left: Illustration of x-ray transmission imaging with the radioactive source placed at the bottom of a water-jet drilled hole. Right: Illustration of x-ray imaging with a thin-tube x-ray generator inserted into an enlarged water-jet drilled hole.

Figure L.10—Two Illustrations of X-Ray Imaging

A larger system using deeper sources might be used as the primary method of locating mines.

The use of a radioactive source raises the question of the environmental risk in the event that an accidental detonation destroys the equipment and scatters fragments of the source. Using a gaseous radioactive source, such as the long-lived krypton-85, which emits 0.514 MeV gamma rays, could mitigate this hazard. In the event of damage to the source, the krypton gas would dissipate, leaving no contamination of the surrounding soil.

TYPICAL PROGRAM PLAN

To investigate the potential techniques described in the previous section, AS&E would follow a program task outline as described below, with a nominal schedule as shown in Figure L.11.

Tasks include the following:

1. **Problem Definition:** What specific type of mine needs to be detected in this program? What are its characteristics? How is it deployed? What is the nature of the surrounding area—soil, rock, etc.?

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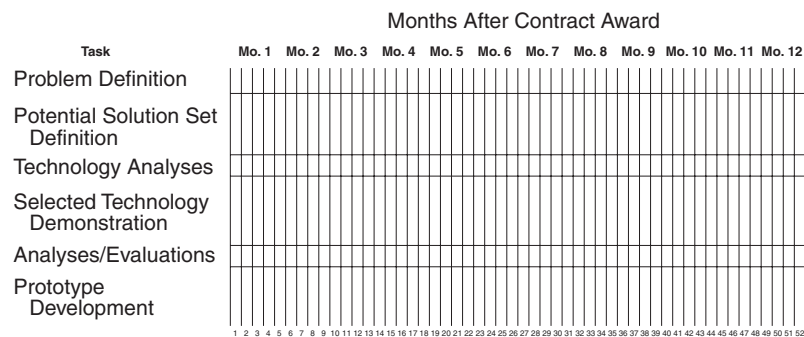


Figure L.11—Nominal Program Schedule

2. **Potential Solution Set Definition:** How could this problem be solved? Identify the methods under consideration and briefly describe them.
3. **Technology Analysis:** Identify the advantages and disadvantages of each technique under consideration. Qualities should include: technology maturity, projected operational concept, type of mine detected, known or suspected limitations, speed of operation, false alarm rate, projected system price, and life-cycle cost.
4. **Selected Technology Demonstration:** Design and implement a quantitative and qualitative test program that will provide representative data about the selected technology.
5. **Analyses:** Analyze the results of the demonstration and provide a report containing results and recommendations for future work.
6. **Prototype Development:** Design, fabricate, and test a system that incorporates the selected technology.