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X-ray Imaging for Homeland Security

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***Abstract*—Since 9/11 there has been a growing interest to improve the security both of air travel and of cargo shipping. Visual inspection is the simplest tool and is very efficient, when single objects of small size are to be checked. The complexity of inspection increases as we have large "boxes" and when several objects are packed into a closed space, such as in a luggage or even in larger volumes like shipping containers or trucks.**

An obvious method to check these objects is using x-rays, which can penetrate through the shipping "boxes" and let us see what is inside. It is well known that the x-ray absorption of an object depends on the absorption coefficient and the thickness of a given material. So X-ray is an excellent tool to check luggage without opening and manually checking each of them. This paper gives an overview of different x-ray luggage inspection techniques from simple transmission imaging to multi-energy and 3D x-ray computer tomography (CT). However, none of the x-ray imaging methods give a full differentiation between a plastic explosive and a bag of flour of the same shape. X-ray diffraction is a more sophisticated method to differentiate materials with and without crystalline structure and among materials of different crystalline structures.

There is also a real danger that not only traditional explosives but nuclear materials can be smuggled into the US in cargo containers and trucks. Not only the explosion of a nuclear bomb but also a so called "dirty bomb" could cause death and panic in large cities. So to check the containers before they enter the country, for explosives and especially for nuclear materials is a primary goal. As it was mentioned earlier the x-ray absorption of the materials depends on the x-ray energy. Higher energy mega-electronvolt x-rays can penetrate through thick steels and other highly absorbent materials. This makes it possible to check the content of shipping containers or trucks with steel walls in the loading area. The theory and limits of high energy x-ray imaging, dual energy x-ray imaging, and high energy CT are also demonstrated.

A further application using x-rays is back scatter imaging. This technique is especially useful for detection of landmines and IEDs (Improvised Explosive Devices) as it will be shown below.

Finally, the use of neutron detection for identifying nuclear materials will be mentioned. Neutron detection is a viable alternative to x-ray imaging for finding nuclear materials.

Keywords-component; homeland security, measurements with X-rays, imaging, x-ray imaging, X-ray radiology, imaging detectors, Flat-Panel imaging arrays.

I. LUGGAGE CHECKING WITH X-RAYS

The simplest x-ray method for checking luggage is radiographic x-ray imaging. It can be done either by a single radiographic shot with a large area imager or by a continuous x-ray exposure and using an x-ray line sensor. Generally the line scanning method is used in the case of carry-on luggage scanning. It requires only a limited area to be illuminated by x-ray and because the carry-on items are continuously travelling on a belt drive it allows continuous scan and storage of the x-ray image of the whole luggage. Because the illuminated area is narrow line it is much easier to shield the x-rays than in the case of a single shot x-ray system, where the whole object is illuminated. A typical line scanning setup is shown in Fig. 1.

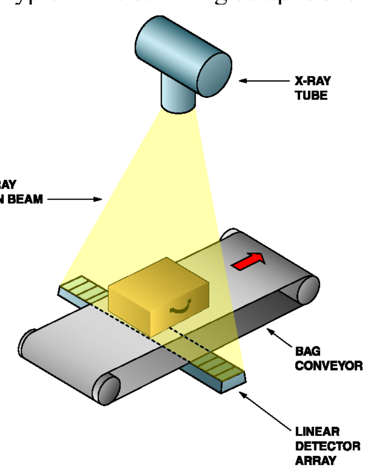

Fig. 1. Luggage line scanner

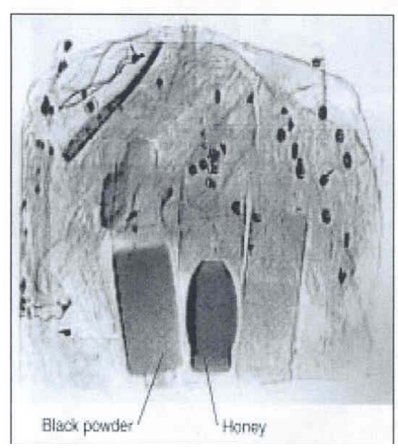

Fig. 2. Discrimination is a big problem

The main advantage of the linear scan system is the high speed, up to 1500 luggage/hour. The main drawback of the single radiographic line x-ray scanning is that the black powder gives the same x-ray shadow as the honey (see Fig. 2). Moreover, in a single view the objects are overlapping each other and it would be difficult even to identify a simple gun by shape, if some other highly absorbing material is covering the gun. It is known that x-ray absorption of different materials has different dependence on x-ray energy. So using x-rays with two different average energies it is possible to differentiate between different density materials. So this is why dual energy x-ray systems are applied at the airports. Moreover, if we use an x-ray source rotated 90 degrees; we can also eliminate some of the overlapping object problems.

However, we still have two other problems:

1. High positive rate in explosive detection and especially
2. Very hard to detect explosives in sheet form (plastic explosives).

A significant improvement of checking bags with questionable contents is gained through x-ray CT imaging. In this case the x-ray tube and the detector rotate around the luggage. Using a single or multi-slice detector (and a slowly moving bag on a container belt synchronously with the rotating x-ray system) we have a spiral CT system. Another method for generating an improvement in bag checking is to image the luggage with a cone-beam CT x-ray system. The luggage remains stationary and is shot by a large area x-ray detector, which covers the whole luggage. By collecting 360 or more images per rotation and using reconstruction software we can get 3D images of the objects. X-ray contrasts of the objects inside the luggage does not depend on the thickness of the object only on the material i.e. absorption coefficient or so called Hounsfield unit = HU. Per definition the Hounsfield unit of the water is 0, the air has -1000 value and more absorbing materials (like metals) have Hounsfield units in the range of 0 - 2000. Therefore, the CT method is a very good tool for discriminating between different materials. However, taking CT images and reconstructing them is rather time consuming so it is not practical to check all of the luggage by this method. It is used only as a tier two system, checking that luggage, which has been deemed questionable by simple x-ray imaging.

The CT scanner is capable of separating superimposed objects but it has severe problems detecting explosives in sheet form and it is hard to differentiate between a fruit cake or cheese and plastic explosive, which have similar absorption coefficients. CT scanning still provides a high rate of false positives.

It is known that Compton backscatter depends on the material content. So an additional option is to use x-ray backscatter imaging for better material identification. But even this method is not perfect.

Moreover, we know that many explosives (and illegal drugs) give intense x-ray diffraction patterns. X-rays are diffracted at precise angles and intensities from microcrystalline materials. We can get material specific x-ray diffraction patterns. This method is also sensitive to small quantities of material.

X-ray diffraction techniques are a well known method of analyzing crystalline structures. Classical x-ray diffraction takes place from the atomic layer planes in crystals. In accordance with the Bragg equation, constructive interference takes place when:

$$2d\sin\theta = \lambda(n);$$

where, λ is the x-ray photon wavelength, d is the atomic layer plane spacing, and θ is the diffraction angle. The d-spacings of the atomic layer planes are substance-specific and diffraction data provides a non-contact x-ray fingerprint for identifying crystalline materials. Most explosives and many illegal drugs are crystalline substances. Even "plastic explosive" contains a high explosive such as PETN in powder form, which is highly crystalline on a micro-scale, dispersed in a soft binder of polyurethane and wax.

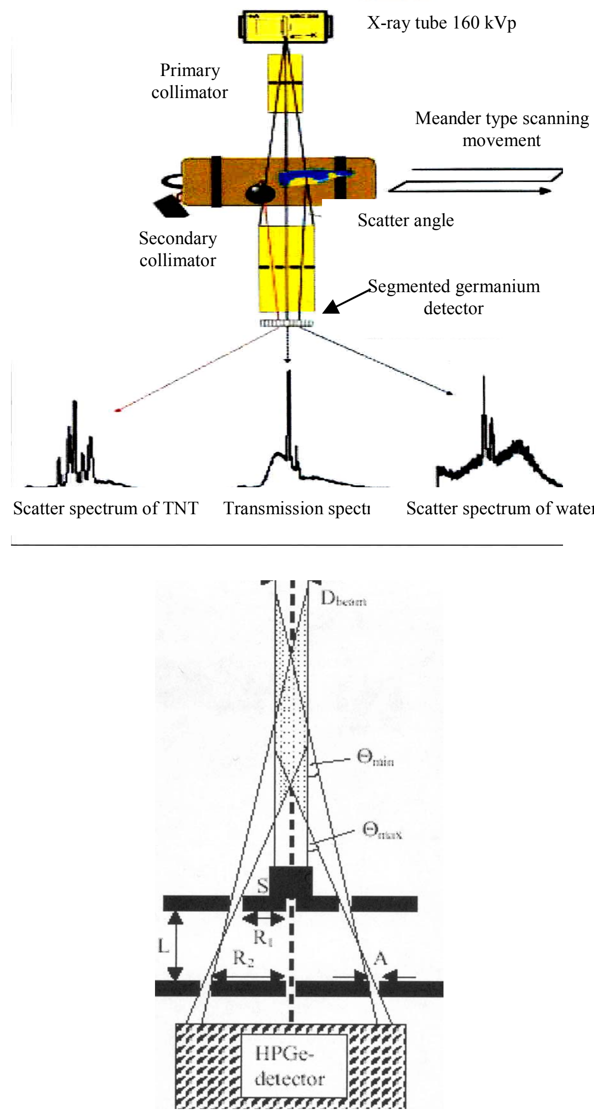

Fig. 3. The Yxlon scanner

General x-ray diffraction measurements are made with monochromatic (cupper K alpha of about 8 keV) x-ray beams. The problem with of using this for luggage screening is that the 8 keV x-rays are absorbed by any material even air so they do not penetrate far through a piece of luggage. Moreover, it is very difficult to generate a higher energy monochromatic x-ray beam without a very expensive accelerator. So one solution is to use polychromatic x-rays and applying an energy resolution detector set up at “stationary” 2θ and applying the Bragg law for different energies (different λ values). This method is the basis of the Yxlon system (Yxlon GE), which uses a polychromatic x-ray source and a cooled germanium detector with good energy resolution. As illustrated in Figure 3, a narrow, collimated x-ray beam passes vertically downward through the bag. The collimated pencil beam is meander-scanned through the luggage and the diffracted beam is sensed by a high purity segmented Ge detector cooled to liquid nitrogen temperature. The x-ray photons follow paths with minimal divergence laterally. Where the beam intercepts crystalline material, x-ray photons are diffracted away from the beam. The trajectories of the diffracted photons lie on cones that are centered upon the beam axis. The segmented germanium detector below the conveyer belt collects the diffracted x-rays. A secondary collimator is placed in front the detector having a narrow acceptance angle for x-ray photons. The collimators ensure that each pixel of the germanium detector views a separate small area of the beam slice, thus dividing it into voxels. The beam defines a vertical slice running transversely through the bag, and the segmented germanium detector views the entire slice. By collecting the diffracted x-rays from each voxel it is possible to detect, identify and physically locate explosives and other prohibited materials within the bag as it moves through the x-ray beam. Spectra of different materials are quite distinct and different substances, explosives and even illegal drugs can be separated by their unique x-ray diffraction pattern.

Fig. 4. GE Yxlon scanner based on this technology

Fig. 4 shows an Yxlon-GE XRD luggage scanner. The scanner is very sensitive to detect explosives but the drawbacks are that it is very expensive, requires significant amount of time to check one suitcase and needs special cooling systems for the sensitive Ge detector. Consequently, it is used only as a third tier system, scanning luggage that was previously scanned by simple x-ray and/or CT and suspicious object(s) had been found that could not be identified by these methods. To save time the XRD machine scans the suspicious parts only.

Checking for nuclear materials in carry-on luggage is generally not practical because of the difficulty of hiding and shielding nuclear material in a relatively small volume.

Other, non x-ray based scanning methods for explosives also exist for luggage and traveler checking. Such methods like gas chromatography, electronic - magnetic testing methods for metal objects and Terahertz technology can be employed for scanning people without ionizing radiation to find out what is hidden under their clothes. The goal of this paper is to concentrate on x-ray based techniques so it does not cover these other methods.

II. CHECKING LARGER OBJECTS BY X-RAYS

In 2007 over 18.5 million TEU (Twenty feet Equivalent Unit) containers filled with different goods arrived to the US just by sea. That is more than 50,000 a day! This number does not include the containers shipped by trucks from Canada or Mexico and the large number of smaller containers shipped by air. Only a small percentage of these goods had been checked!

In cargo containers and truckloads, larger amount of explosives and even more dangerous special nuclear materials, materials for making weapons of mass destruction, can be hidden. So the other main goal for homeland security is checking larger shipping objects, like cargo containers for air, sea and land shipping.

Fig. 5. Photo of Colombo Express, which was one of the world largest container ships in 2005.

As previously mentioned, the x-ray absorption coefficient is highly dependent on the x-ray beam energy. Higher energy x-rays can penetrate through otherwise highly absorbing materials like metals. The big shipping containers have thick, generally 1/8 or 1/4 inch (3.2 - 6.4 mm) thick steel metal walls. To scan these containers, x-rays have to penetrate through the thick metal walls and check what is inside the container. Moreover, we may have some heavy machinery and other metal objects inside the container. For scanning tasks we need very high energy x-ray sources in the mega-electronvolt (MeV) range and imagers suitable for efficient detection of high energy x-rays. Figure 6 shows the depth of the x-ray penetration versus energy for steel. From this figure we can see that 9 MeV x-rays can penetrate over 300 mm thick of a steel object. The absorption of some high Z (high atomic number) materials such as of tungsten (W) or tantalum (Ta) could be higher so the penetration depth is smaller for these materials.

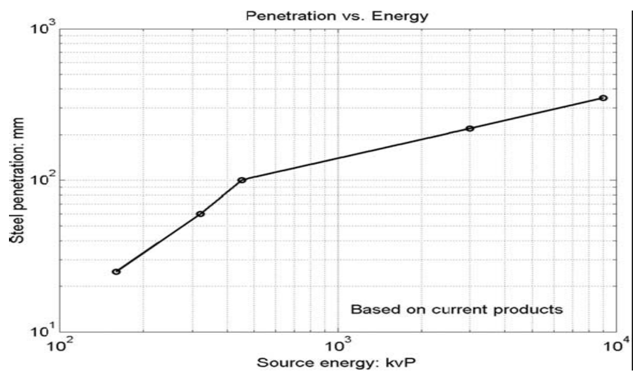

Fig. 6. Steel penetration versus x-ray energy

A large container can include very different materials, from clothes to heavy machinery. The digital imagers can have 14 bit (16,384) grayscale resolution. However, the regular displays can show only 256 levels. So it is very important how compression of the full dynamic range to 256 levels for imaging is done to see different objects.

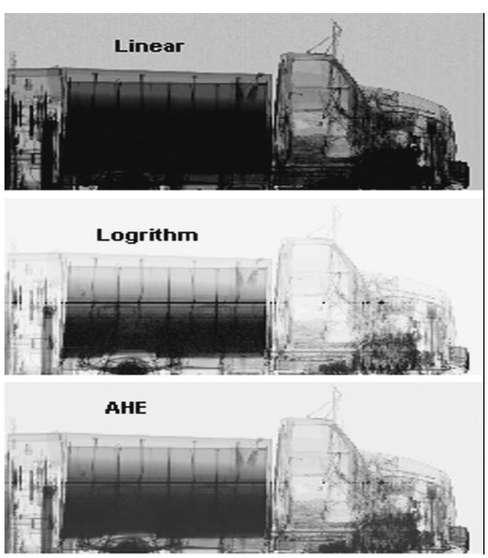

Fig. 7. Image of a fuel truck at Logan airport (G. Chen / Nucl. Instr. and Meth. in Phys. Res. B241 (2005) 810–815).

Figure 7. gives an example of three different image displays of the same object, which is a fuel refilling truck for airplanes, mapped to 256 gray levels. The tank is partly filled with fuel. With linear scale only the thinner objects are visible and the rest of the truck looks black. Logarithmic scaling provides a much wider dynamic range but now some of the thinner objects are not so visible. Finally the bottom image was scaled with an adaptive histogram equalization program. This provides the best visibility of all of the details of the truck.

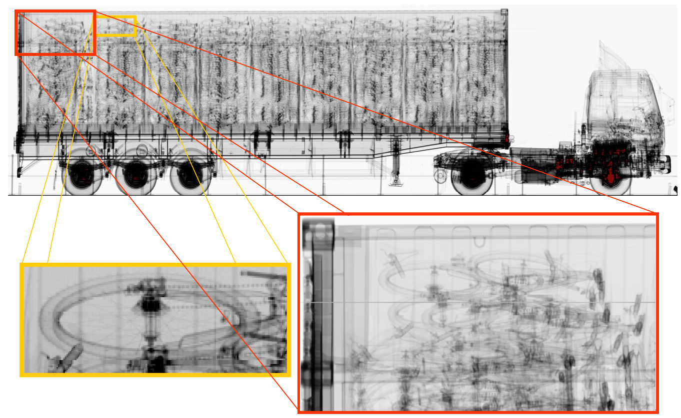

Fig. 8. Spatial resolution is still very good can be as high as 2 mm.

The spatial resolution is also an important factor in the case of smaller objects or object identification. Higher resolution is required for discrimination among small objects. Figure 8 gives a good example. This general image of a truck (top image) does not provide enough information about what is inside. Some image magnification shown on the right bottom part of the image provides a hint that it might be a shipment of bicycles. Further magnification on the left clearly shows the wheel of a bicycle. Even the rays are clearly visible.

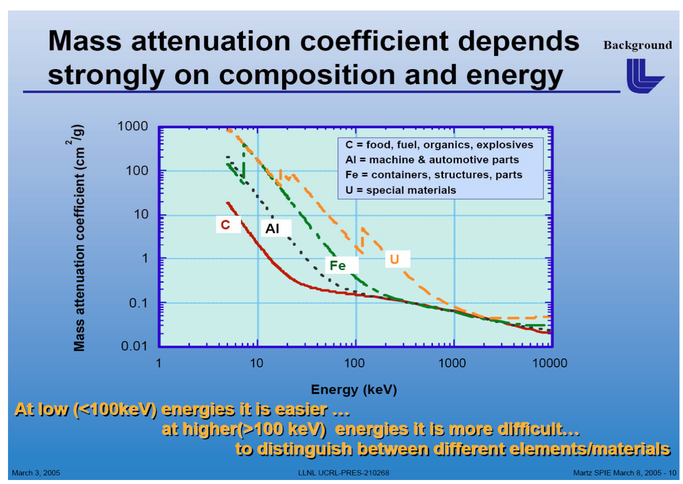

Fig. 9. X-ray attenuation coefficient as a function of energy for a few materials.
(LLNL UCRL-PRES-21268 SPIE March 2005)

So we need high penetration depth and at the same time good spatial and contrast resolution. As shown above, very good resolution and contrast can be achieved at high energy x-ray imaging but the same problem of differentiation between different materials as for low x-ray energies still exists. The most obvious solution is to use imaging at two different x-ray energies as it gives good discrimination for luggage inspection. Figure 9 is a graph of x-ray absorption curves of different materials. It is clear that we have large absorption coefficient differences at the keV x-ray energies but the differences at the MeV energy range are much smaller. However, dual MeV energy imaging is still one of the best and most proven methods for material discrimination in large containers and trucks.

Fig. 10 is an example of how we can discriminate between different materials inside a truck using dual energy imaging. Different materials are color coded. This method is not perfect because the flour has the same color as diesel fuel or fruit, but heavier elements such as steel and lead are easily distinguished from the lighter elements even if they are thin. An additional problem is the overlap of different objects. A better solution is a MeV energy CT system. Such systems exist in design (see for instance Fig. 11) but at present the cost of building such a huge CT does not make it competitive. Furthermore, it would slow down significantly the scanning rate so it is better applied as a tier two system check if something suspicious is found by line scanning. However, the CT scanning method has been used already for air cargo screening, where the size of the cargo containers are much smaller and lower MeV x-ray sources and smaller imagers can be used making the system less expensive.

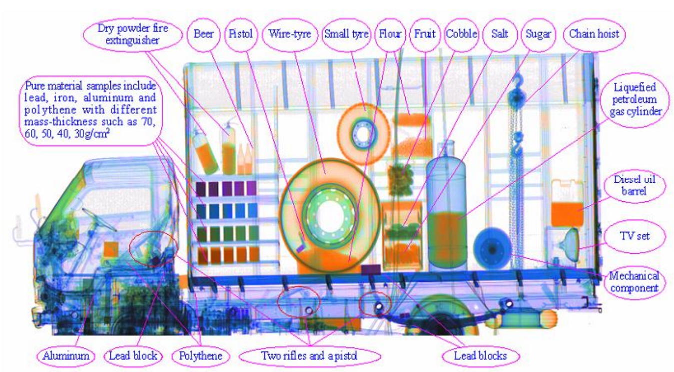

Fig. 10 Image taken by a dual energy cargo inspection system (Proc. of LINAC 2006, Knoxville, Tennessee, USA)

Further large threats are the special nuclear materials (SNMs). Even small amounts of radioactive materials can be very disruptive. Source strengths of 1-1000's of Curies are already big concerns not only as nuclear bomb but as the so called dirty bombs. Just 3 Curies of gamma emitter (this is only fractions of a gram) spread over a square mile would make the area uninhabitable since the dose would exceed the maximum incremental dose for general population (it is at present 0.1rem/year EPA limit – in comparison a CT scan is 2-3 rem). In this latter case the health effects are minimal; the psychological and economic effects are more dominant. Gram for gram comparison, radioactive materials can be as disruptive as weaponized anthrax, but nowhere near as dangerous for health. Larger amounts (>100 gram) of uranium and plutonium are possible sources of weapons of mass destruction (WMD) and it is of great importance to find these

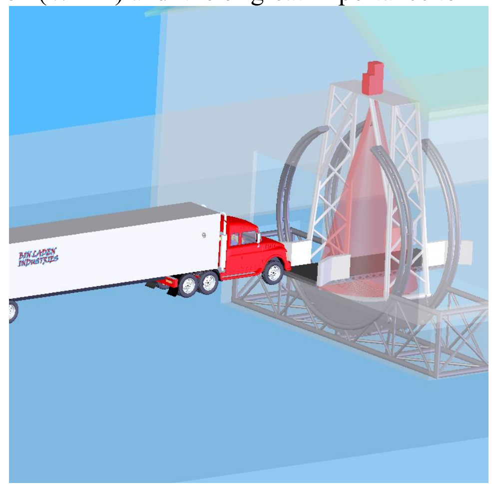

Fig. 11. A schematic of a truck scanning CT system with large area cone beam CT system

volumes of materials in containers and trucks. To detect radioactive material, detectors that respond to gamma and/or to neutron radiation may be used.

Figure 12 shows a typical nuclear detection system at a land border crossing using both neutron and gamma detectors. The main problem is that smaller amounts of nuclear materials are generally easy to shield both for gamma and neutron radiation. High Z materials like lead (Pb) are good x-ray and gamma ray absorbers and high H, B or Li content

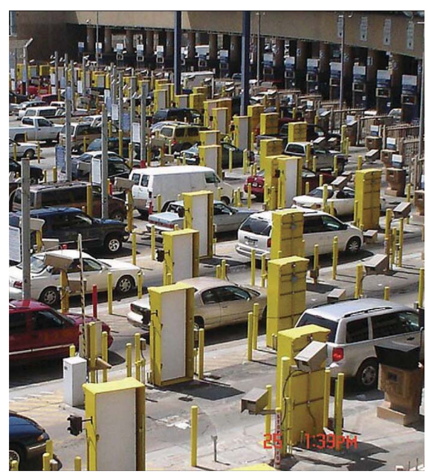

Fig. 12. A typical nuclear detection system incorporating radiation detection technology at a land border crossing. (Materials Today March 2008. Vol 11. No. 3)

materials are good absorbers for neutrons. So in this case, the x-ray imaging helps again. If we see a large volume of high Z materials or large volume of light materials, like polyethylene type materials in a container, then it should raise suspicion that those materials may shield some nuclear materials and further investigation is necessary. One new method for detecting nuclear materials is to use MeV energy x-ray pulses over 6

MeV energy, which generate fission in nuclear materials. Some of the fission products, neutrons and delayed gamma rays can be detected and they could give characteristic information about the specific nuclear material inside the cargo.

Several other neutron imaging methods exist such as thermal neutron analysis (TNA), fast neutron analysis (FNA), pulsed fast neutron analysis (PFNA) and pulsed fast neutron transmission spectroscopy (PFNTS). Details about these techniques are beyond the scope of this paper.

III. CHECKING FOR LANDMINES AND IEDS BY X-RAYS

Finally a few words about still another important threat, which killed thousands of US solders in Iraq: these are land mines and similarly Improvised Explosive Devices (IEDs). Land mines are generally professionally manufactured explosives used against tanks, trucks and other vehicles. The IEDs as the name suggests are amateur-make explosive devices but they are as dangerous as the landmines. Those devices, if they contain enough metal parts can be detected by similar but more professional RF devices that the "treasure hunters" use to find metal objects in the ground. A more sophisticated method uses the Compton back-scatter method for landmine and IED detection as shown in Fig. 13. The primary collimator can be moved both in the plane of the drawing (see arrows), to access differing depths underground as well as in the y direction perpendicular to the plane of the drawing.

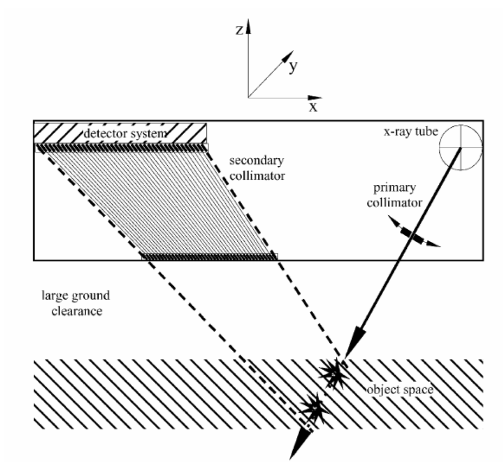

Fig. 13 Schematic illustration of Compton back-scatter system for landmine detection.

Generally the whole scanning system is installed onto an arm of an armored vehicle and hangs well ahead of the front of the vehicle. To get good images one has to correct for the depths of the devices in the ground because of the exponential absorption of x-rays in the ground both for photons travelling from the x-ray tube towards the object and for the backscattered signal coming from deeper in the ground. Fig 14 is a good example of such imaging.

Fig. 14. Compton back scatter image of anti-tank mine (type TM-62). (G. Hardling Radiation Physics and Chemistry 71 (2004) 869.

Other, neutron beam activated methods are also used for landmine detection, mostly to find the characteristic gamma radiation of nitrogen (N), which is a basic element in TNT and RDX explosives but detailed discussion of those are beyond the scope of this paper.