Detection of Land Mines Using Lateral Migration Backscatter X-ray Radiography

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ABSTRACT

An X-ray mine imaging system (XMIS) that uses a new form of backscatter x-ray radiography developed at the University of Florida was successfully field-tested at Fort A.P. Hill, Virginia in October, 2001. The XMIS obtained high quality images of both anti-tank and anti-personnel mines on several of the Fort A.P. Hill test lanes. For high resolution imaging at a power level of 750 watts, total time for scanning and for processed image acquisition was about 60 s for a 0.5 m x 0.5 m area. The very good imaging results obtained from the initial field tests with the XMIS demonstrate the excellent capabilities of this system as a confirmation sensor for land mine detection. Critical to the success of the XMIS is the use of both collimated and uncollimated detectors. This yields system capabilities and performance that cannot be matched by using only uncollimated detectors with coded apertures and spatial filters to deconvolve system response. The initial field tests showed that some fairly simple modifications could significantly improve the performance of the XMIS. With the modifications, high resolution scanning of a 0.5 m x 0.5 m area can be done in 20 to 30 seconds at a power level of around 300 watts.

Keywords: land mine detection, Compton backscatter, x-ray imaging, confirmation sensor

1. INTRODUCTION

Development of the imaging concept used in the present work began when Fort Belvoir personnel proposed to the University of Florida (UF) that a particular variant of x-ray Compton backscatter imaging (CBI) be applied to the difficult problem of buried, plastic land mine detection. The new CBI method developed at UF[1-10] and used to obtain the signatures of mines has been given the name lateral migration radiography (LMR). Unlike conventional CBI techniques which utilize only single-scatter photons, LMR uses both multiple- and single-scattered photons. LMR requires two types of properly configured detectors. Uncollimated detectors image primarily single-scatter photons while collimated detectors image predominately multiple-scatter photons. This allows for the generation of two separate sets of images. The uncollimated detector image contains primarily surface or near-surface features while the collimated detector images also contain subsurface features. These two image sets make LMR useful for imaging and identifying objects to depths of several x-ray photon mean free paths (~10 cm) even in the presence of surface clutter. The use of both detector types allows for the removal of the effects of ground-surface variations and an ability to make the system relatively insensitive to source/detector standoff variations.

The collimated detectors are designed to especially admit those photons that scatter towards the detector position, passing laterally (with respect to the illumination beam) through an object before having further scattering in the object. Low atomic number or low density in such lateral paths yields a high detection probability. When laterally-moving photons encounter air volumes, they free-flight across the void resulting in a significantly higher detection probability in the collimated detectors. For land mines, the relatively low atomic number of plastic and the very low density of air volumes give bright or high intensity image components. In contrast, even a small amount of metal yields a significant decrease in image signal intensity. Although the signals in collimated detectors are much less intense than those reaching uncollimated detectors, they are less easily corrupted by surface clutter and provide an increased signal-to-noise ratio, often dramatically higher, than achieved with uncollimated detectors.

With uncollimated detectors, surface clutter can prevent first-collision photons from reaching the detector and lead to multiple-collision photons entering the detector. Because of this corruption, images of a buried feature when there is unknown surface clutter do not uniquely represent the surface and regions underneath and complex algorithms are required to extract useful information. In order to reduce this corruption and better correlate single-collision photons with a specific location for the formation of an image, apertures can be employed. Even so, there is still significant corruption and this leads to the use of coded apertures with spatial filters to deconvolve the uncollimated detector response. The use of apertures imposes a constraint on detector size and detector mode of operation. Uncollimated detectors employed with apertures are normally relatively small area detectors and operate in a voltage or counting mode rather than in a current or integration mode. This reduces the attainable signal intensity and the use of apertures further reduces the number of photons as does the application of masks in the decoding process. An aperture, like a detector collimator, passes only photons with a selected behavior, thereby reducing the imaging signal intensity. However, the aperture approach also rejects a lot of extremely valuable information carried by multiple-collision photons. It is important to recognize that with increasing depth, photon-for-photon, multiple-collision photons are more important than single-collision photons in that they carry more detailed information. A key point is that once valuable information has been thrown away, even very sophisticated and time-consuming processing is not going to recover this. And if sophisticated processing can generate an acceptable image when valuable information has been rejected (as with the "uncollimated" detector, coded aperture approach), this level of processing effort will provide an even better image when applied to a method that hasn't discarded this information.

An important collimated detector image signature phenomenon is lateral migration shifting. When the x-ray beam is scanning towards the mine, the front collimated detector registers an increased signal relative to the other directions. Similarly when the x-ray beam is moving away from the mine, the rear collimated detector registers an increased signal. The highest intensity in the front collimated detector shows up earlier than for the rear detector which gives the appearance of backward shifting for the front detector image. For the rear collimated detector there is a corresponding apparent forward shifting of the image. The shifting increases with the mine depth-of-burial (DOB) and can be correlated to indicate the mine DOB.

An objective of the research for this program was to develop an LMR system concept and preliminary design that could provide a unit for initial field-testing. This LMR system design includes an x-ray generator with articulating collimator, three x-ray detector panels, a computer with a data acquisition board and display, digital control electric motors to provide articulation and positioning, and an electric power generator all mounted on a suitable vehicle platform. The resulting system has been named the X-ray Mine Imaging System (XMIS). XMIS was employed on the vehicular test lanes at Fort A.P. Hill, Virginia in October, 2001 and results from these field tests are included below.

With regard to the design of the XMIS, it should be mentioned that the original testing plan was to use the XMIS for performance of "geological" investigations at selected locations of ground penetrating radar (GPR) false alarms. In this mode, the XMIS was to be cantilever-supported by a forklift when doing a 0.5 m x 0.5 m scan of one of the selected locations. Following the initial scan, a few cm of soil was to be removed, the XMIS would be lowered by the forklift a few cm and the area would be scanned again. The goal was to help determine the source of the GPR false alarms at the selected locations through a series of carefully obtained images with each image showing a few cm of depth. This mode of operation was never implemented because upon arrival at Fort Hill it was decided that the lanes of interest were needed in the coming weeks for further mine detection testing and the soil could not be disturbed.

2. THE X-RAY MINE IMAGING SYSTEM

For XMIS, the forced-air-cooled version of the LORAD LPX-160 constant potential x-ray generator provides an excellent source from the standpoint of performance, size and weight. The LPX-160 is a rugged, commercial x-ray tube designed for field inspections of pipe welds. The LPX-160 has a maximum x-ray spectrum energy of 160 kVp and a maximum power level of 800 watts. The optimum x-ray source energy for the detection of mines with backscattered x-rays in typical soils is in the range of 120 kVp to 160 kVp. Good imaging quality requires about two million source x-rays per pixel and this translates into an electric energy requirement of one joule per pixel. A pixel size of 15 mm by 15 mm provides good resolution for both antitank (AT) and antipersonnel (AP) mines and for image scan times on the order of 10 to 100 seconds, the required x-ray generator power level is found to be 100 to 200 watts. The weight of the air-cooled LPX-160 tube head is 15 kg and the weight of the control unit is 16 kg. The tube head is 18.4 cm in diameter and 77.5 cm in length. The control unit is 30.5 cm by 26.7 cm by 45.7 cm.

A significant accomplishment in this research effort was the development of an x-ray source collimator design that uses a continuously rotating cylinder to synthesize a moving aperture from side-to-side with negligible retrace time. Coupled with the x-ray generator forward motion, this provides a raster scan of the ground. This collimator design is a key element in reducing the required x-ray head movement and in obtaining a simple, compact LMR detector system.

Careful detector design and deployment are critical for proper functioning of the LMR mine detection system. High performance organic scintillator block detectors from Bicron, Inc. are used for both the collimated and uncollimated detectors in the XMIS. The uncollimated detector is 140 cm long, 5 cm wide and 2.5 cm thick. The collimated detectors are 140 cm long, 20 cm wide and 2.5 cm thick. The detector collimators are made from 1.5 mm thick lead sheets. Photomultiplier/amplifier/bias-voltage-supply assemblies provide signal amplification and serve as the output device for each of the three plastic scintillator detectors. The photomultiplier tubes attach to the ends of the detectors. The weight of the detector assemblies, including the housing and collimators, is about 30 kg.

Figure 1 illustrates the relative positioning of the LMR components of the XMIS. The x-ray generator with rotating collimator assembly is supported above the mounting platform which is a 1.9 cm thick aluminum plate. Attached to this platform are the detector panel array supports, the digital electric servo motors (not shown in the figure) which provide rotational motion to the x-ray collimator through a belt drive and translational motion to the platform through a lead screw (both not shown in figure), and linear ball bearing assemblies (not shown in figure) that provide translational motion (left-to-right in the figure) of the platform. The linear bearings surround two cylindrical steel rails (length left-to-right, but not shown in the figure). These rails are fixed to the rigid steel frame structure that also provides fixed relative positioning of the limit and safety switches for the platform linear motion. Figure 2 is a photograph of the LMR system as just described mounted on the XMIS transportation vehicle. The mobile XMIS prototype interrogates a square ground surface area of approximately one-half meter side size. For the Fort A.P. Hill tests, the image acquisition time varied from 30 to 60 seconds, depending on the pixel resolution required. For this initial field test, the x-ray generator was run at 150 kVp and 5 ma, i.e., an electric power of 750 watts.

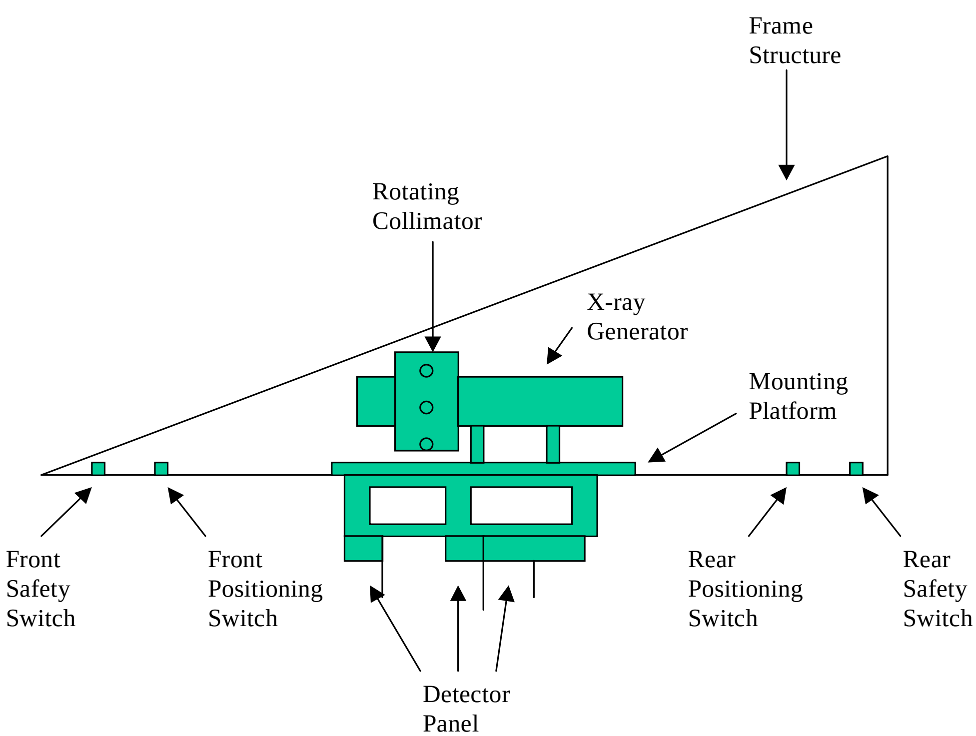

Figure 1: Relative positioning of LMR components of the XMIS.

Figure 2: LMR system mounted on the XMIS transportation vehicle.

3. XMIS IMAGING RESULTS FROM TESTS AT FORT A.P. HILL

This section presents image sets obtained at Fort A.P. Hill using the XMIS. The LMR imaging capabilities make this system well-suited for a mine detection confirmation sensor. To this end, about 30 locations were selected on one of the test lanes at Fort A.P Hill where ground penetrating radar (GPR) methods consistently yielded false alarms. These sites were imaged with the XMIS. Only six of these locations yielded signatures that had any mine-like features, and in only two cases did the image set indicate a possible mine. In addition to image sets of anti-tank and anti-personnel mines, four image sets from the GPR false alarm locations are included herein.

With two exceptions, the presented image sets include the front and back collimated detector images and a processed image. The processed image has had standard digital filtering applied to a cross correlation between the front and back collimated detector images following surface clutter removal by use of the uncollimated detector data. The time required to acquire an image for a ~50 cm x 50 cm area is ~30 s for low resolution and ~60 s for high resolution. This is also the time during which the x-ray generator is actually on. The front and back collimated and uncollimated detector images are acquired real time. The total time required to obtain the processed image is approximately a minute. When viewing the images, the color scheme designation for regions of highest signal intensity to regions of lowest signal intensity is white, red, yellow, green, light blue, dark blue and purple.

Figure 3 shows the image set obtained with XMIS for a TM62P3 AT mine buried flush in dirt on the Fort A.P. Hill S&T Lane 19. The image set includes the front and back collimated detector images and the processed image. This plastic mine has a diameter of 32 cm and a height of 12.5 cm and shows clearly in all three images. Plastic mines give a signal with an increased intensity relative to the signal intensity of the surrounding soil. The high intensity signal in the center of the mine image is due to the presence of void or air in the fuse well region of the mine. This is a distinguishing characteristic of LMR images of plastic mines.

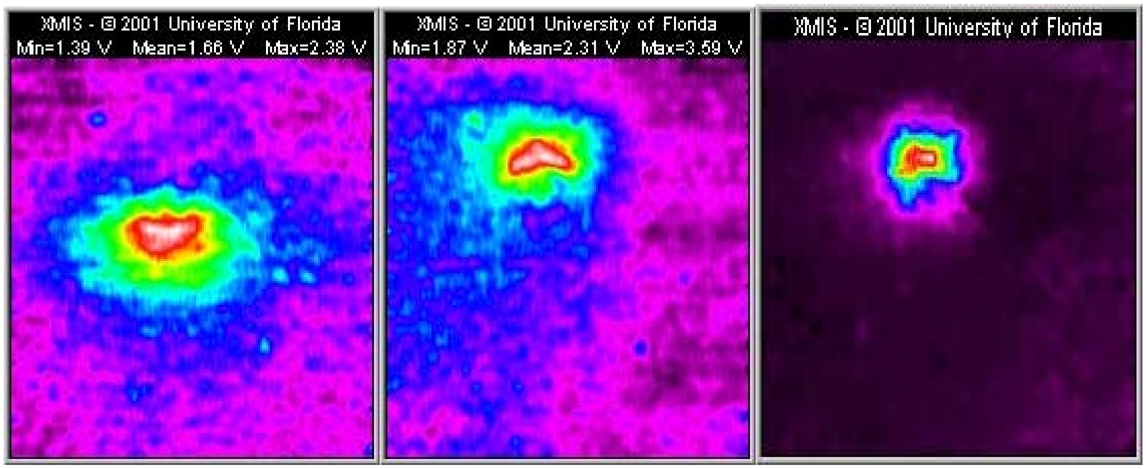

Figure 3: Image set for TM62P3 anti-tank mine buried flush in dirt.

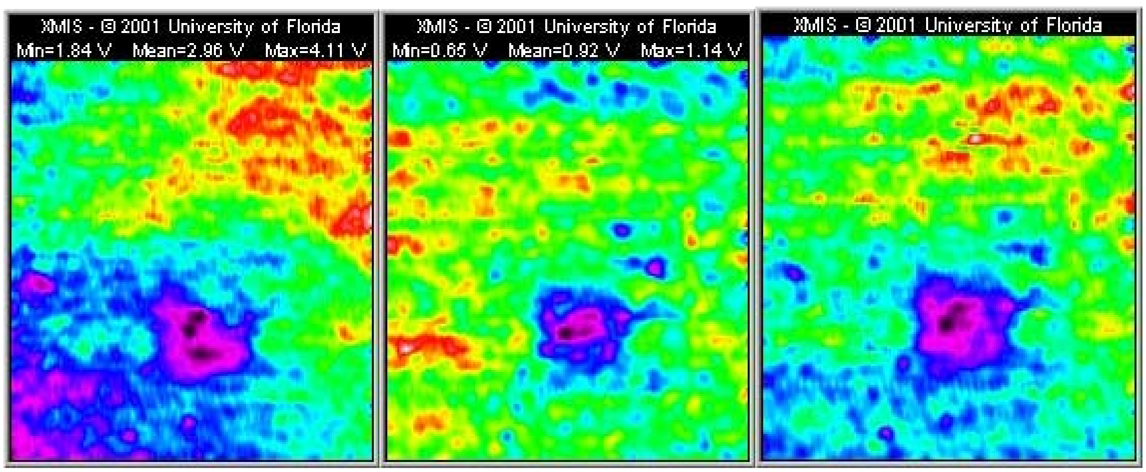

Figure 4: Image set for TM62M anti-tank mine buried flush in dirt.

Figure 4 shows the XMIS image set for a TM62M AT mine buried flush in dirt on the Fort A.P. Hill S&T Lane 19. This image set includes the back collimated and uncollimated detector images and the processed image. This is a metallic mine with a bakelite fuse and has a diameter of 32 cm and a height of 10.2 cm. The mine shows clearly in all three images and because the mine is metallic, the mine gives a signal with a decreased intensity relative to the signal intensity of the surrounding soil.

Figure 5 gives the XMIS image set for a VS1.6 AT mine with a 1 inch depth-of-burial (DOB) in dirt. This plastic mine has a diameter of 22 cm and a height of 9 cm. The image set includes the front and back collimated detector images and the processed image. The mine was located on the Fort A.P. Hill S&T Lane 19 and is clearly visible in all three images.

Figure 6 gives the XMIS images for an M14 AP mine with a 0.5 inch DOB in dirt. This small plastic mine has a diameter of only 5.6 cm and a 4 cm height. The image set includes the front and back collimated detector images and the processed image. The mine is clearly visible in all three images as is the region of increased intensity in the center of the mine due to the presence of the fuse well air space. This mine was located on S&T Lane 19.

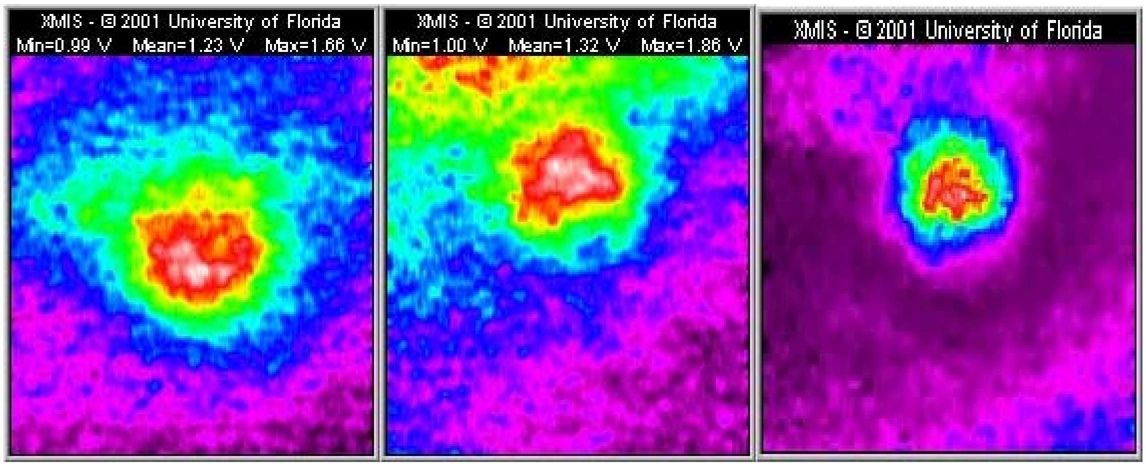

Figure 5: Image set for a VS1.6 anti-tank mine with a 1 inch burial depth in dirt.

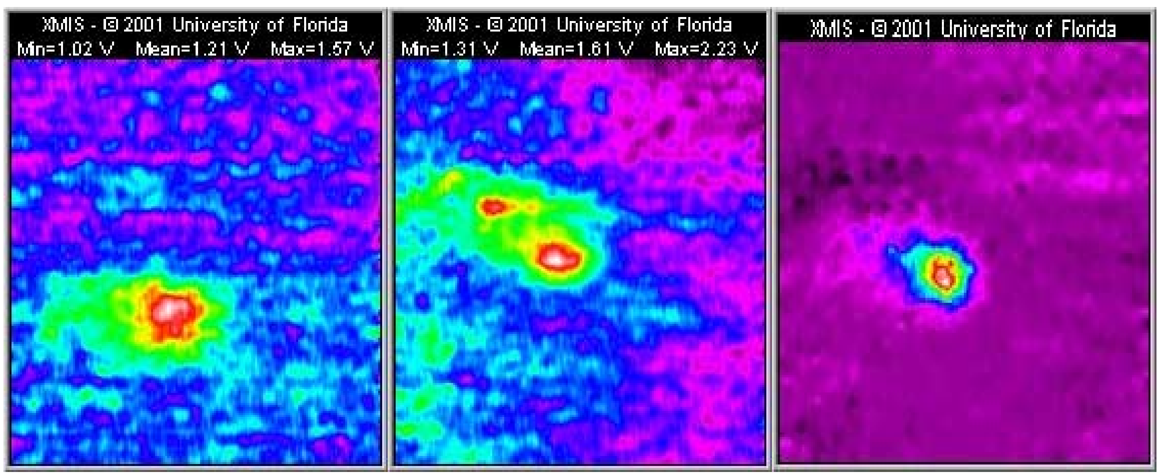

Figure 6: Image set for an M14 anti-personnel mine with a 0.5 inch burial in dirt.

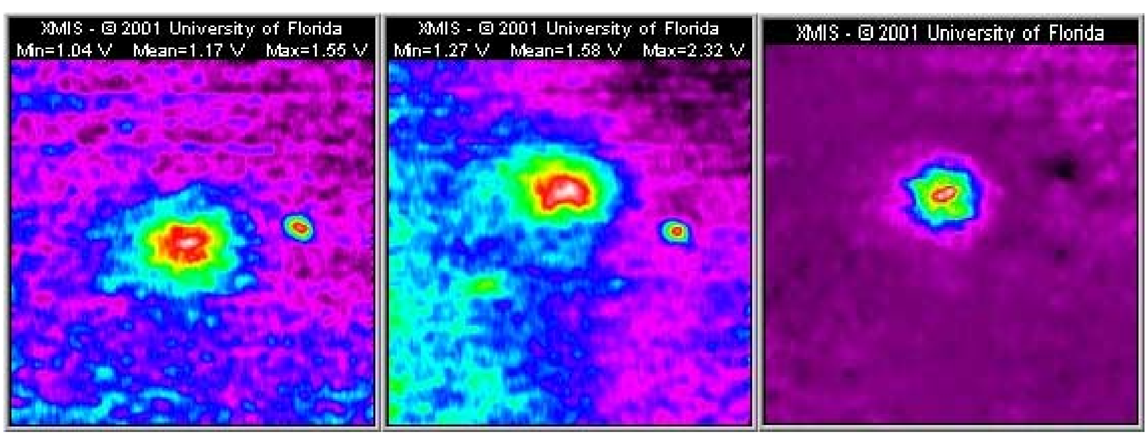

Figure 7: Image set for a TS 50 anti-personnel mine with a 0.5 inch burial in dirt

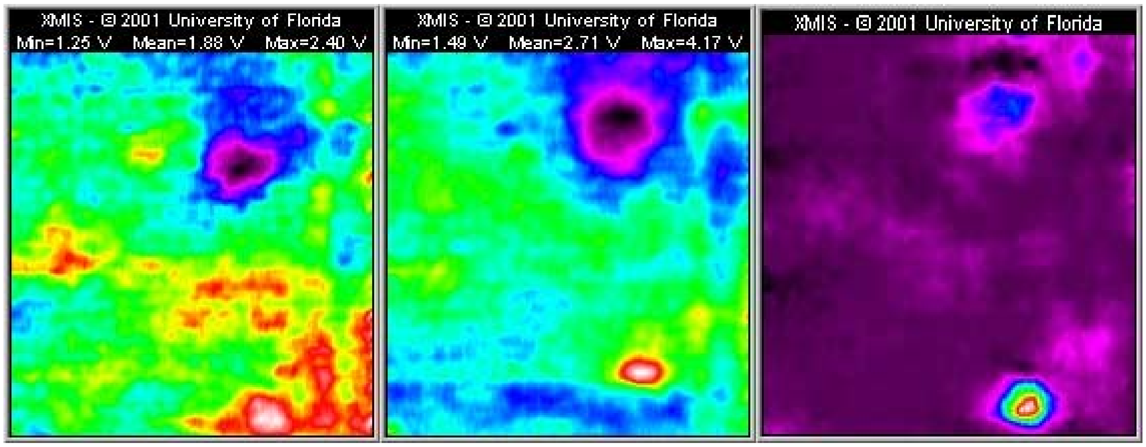

Figure 8: Image set for a TS 50 anti-personnel mine with a 2 inch burial in grass and dirt.

The image set for a TS 50 AP mine with a 0.5 inch DOB is given in Figure 7. This plastic mine has a diameter of 9 cm and a height of 4.5 cm. The image set includes the front and back collimated detector images and the processed image. The mine is clearly visible in all three images. A small surface stone appears to the right of the mine in the collimated detector images. It does not appear in the processed image because the uncollimated detector data has removed this “surface clutter”.

Figure 8 shows the image set for a TS 50 AP mine with a 2 inch DOB in grass and dirt. The image set includes the front and back collimated detector images and the processed image. This is a difficult condition, but the mine is clearly visible on the bottom right in the back collimated detector and processed images. It can also be seen with a bit more difficulty in the front collimated detector image. In all cases there is the characteristic high intensity region in the mine center. The larger region of decreased intensity in the upper right center of the three images is a rock. This mine was located on the Fort A.P. Hill S&T Lane 20.

The XMIS image set for a PMN AP mine with a 1 inch burial in dirt is given in Figure 9. This plastic mine has a diameter of 11.2 cm and a height of 5.6 cm. The image set includes the front and back collimated detector images and the processed image. This mine was located on S&T Lane 19 and is clearly visible in all three images.

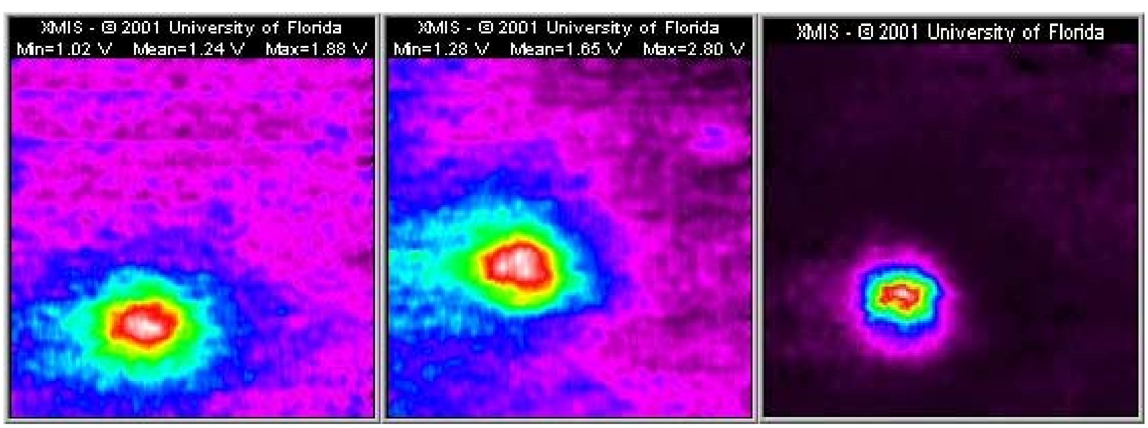

Figure 9: Image set for PMN anti-personnel mine with a 1 inch burial in dirt.

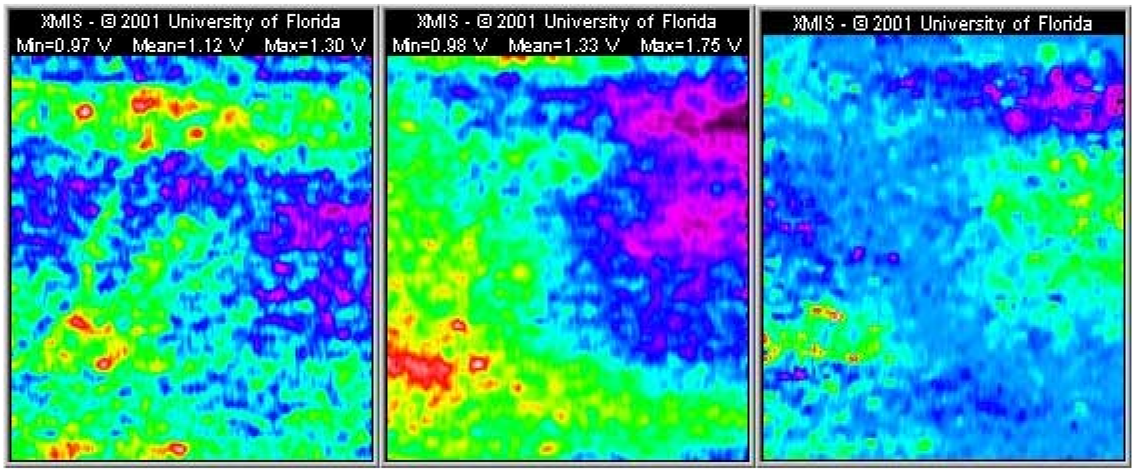

Figure 10: Image set for GPR false alarm position #10.

Figure 10 includes the XMIS image set for GPR false alarm location #10 on the Fort A.P. Hill S&T Lane 3. This pos - ition had one of the highest frequencies of correlated GPR false alarms on this test lane. The image set includes the front and back collimated detector images and the processed image. The back collimated detector image shows a small, elongated amorphous high intensity area at the lower left, but there is no correlation with the other detector images. There is nothing mine-like in these images, just some soil inhomogeneities.

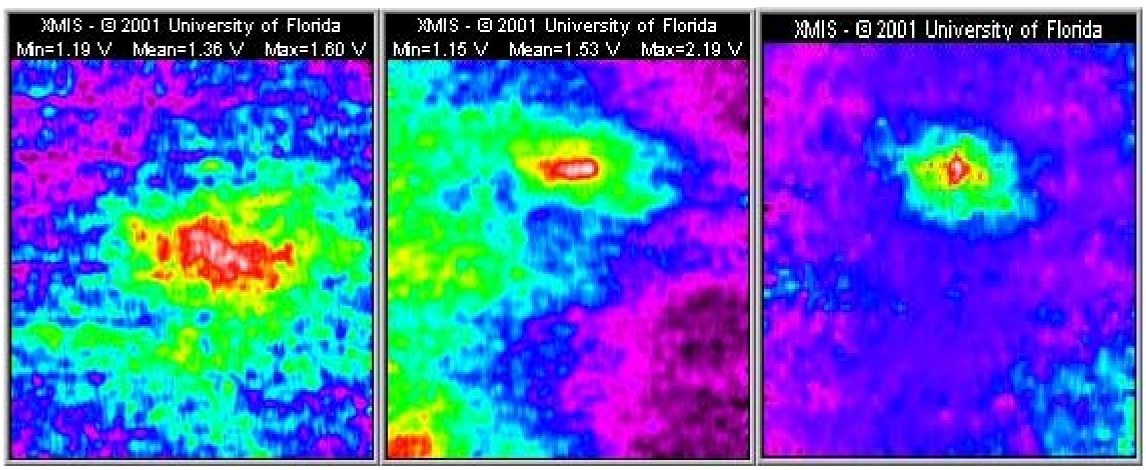

Figure 11: Image set for GPR false alarm position #77.

The XMIS image set for GPR false alarm location #77 is shown in Figure 11. This set includes the front and back collimated detector images and the processed image. There are high intensity areas in the center and upper center of the front and back collimated detectors, respectively. The correlated high intensity area in the processed image has a signature that is similar to that of a deep-buried (~2 inches) AP mine. Of all the examined GPR false alarm locations, this site had the most mine-like combination of LMR images.

Figure 12 presents the image set for GPR false alarm location #105. The set includes the front and back collimated detector images and the processed image. There is nothing mine-like in any of these images, only soil irregularities.

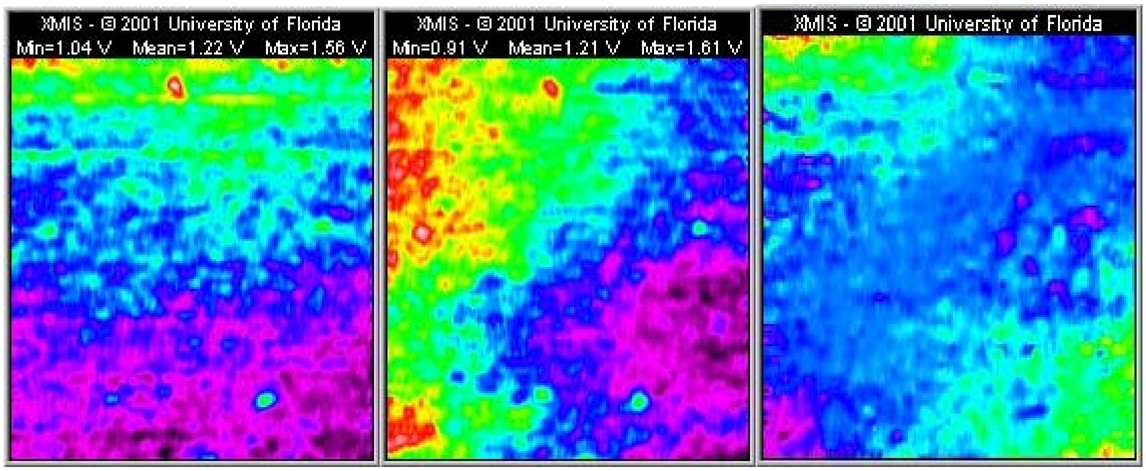

Figure 12: Image set for GPR false alarm position #105.

The XMIS image set for GPR false alarm location #118 is shown in Figure 13. This image set includes the front collimated and uncollimated detector images and the processed image. There is an oval high intensity area in the front collimated detector that correlates with a similar high intensity area in the back collimated detector image (not shown). The processed image shows an oval high intensity area that looks mine-like. However, the uncollimated detector image shows a clear low intensity region at this same location. This combination of LMR image signatures is representative of an area of decreased soil density rather than of a mine. A plastic mine would yield an intensity increase in both the collimated and uncollimated detector images.

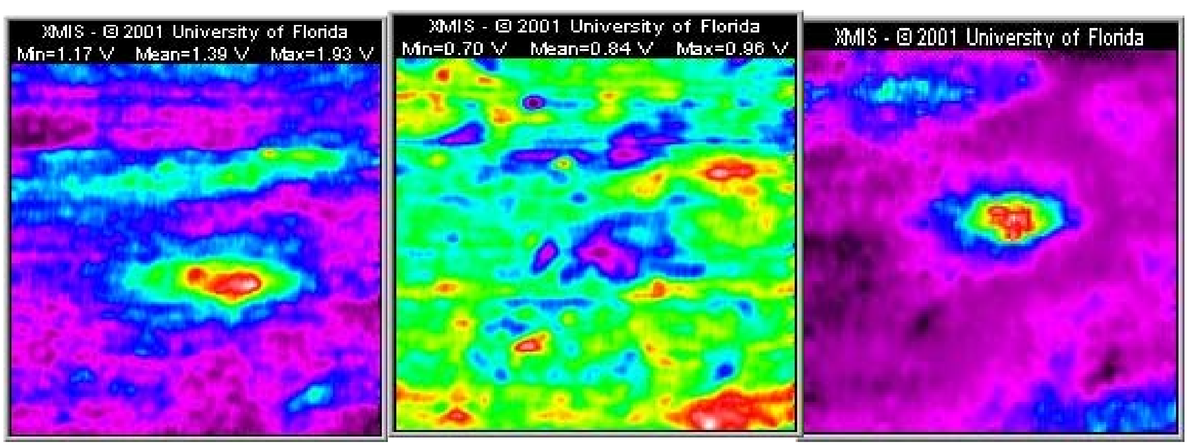

Figure 13: Image set for GPR false alarm position #118.

CONCLUSIONS

The field test results obtained with the XMIS at Fort A.P. Hill were very good and clearly demonstrate the excellent capabilities of this system as a confirmation sensor for land mine detection. These field tests showed that a series of modifications, some fairly simple, could significantly improve the performance of the XMIS.

Following shipment of the XMIS from the University of Florida to Fort A.P. Hill, reassembly and testing of the system showed light leaks in all three of the detectors. The organic scintillator detector blocks are encased in a protective aluminum clad. Some small separations at the seams along the clad edges and a few small dimples in the very thin layer of aluminum on the bottom face of the detector that occurred during shipment and handling and during operation in the field resulted in the light leaks which had to be repaired. A more rugged design for the aluminum casing can eliminate these problems.

The XMIS was designed to provide a 40 to 50 cm wide scan; the very long detector length of 140 cm was used to prevent "edge" effects in the scanned area image. The field testing showed that the detector length could be reduced by 30 % to 40 % without adversely affecting image quality. In addition, the thickness of the scintillator detectors could be reduced by a factor of two. These changes would yield a reduction in weight of the detector assemblies from 30 kg to under 10 kg. Except for the bottom face, the detector assemblies are each wrapped in lead shielding and the lead collimators on the collimated detectors run the length of the detectors. The indicated reduction in detector size would provide a reduction in the amount of lead used on the detectors and an additional weight savings.

Lead shielding is also used around the x-ray generator to reduce leakage radiation from the generator. Such leakage can adversely affect image quality and also increase personnel exposure. A different design for the x-ray generator assembly can reduce the leakage radiation. While this change will increase the weight of the x-ray generator, it will reduce the external lead shielding weight and provide a net decrease in system weight. With the weight and size reductions accompanying the above indicated changes, and because the Unistrut steel frame structure was initially over-designed, the weight of the system frame can be reduced significantly. Heavy (27 kg) forklift extension channels were included in this prototype system to provide a "geological" investigation scan mode capability that was never used. Removal of these channels along with the other above indicated changes would reduce the XMIS weight from 175 to under 100 kg.

Each detector assembly has a photomultiplier tube on each of its two ends for light collection. The location of these tubes makes them vulnerable to physical damage and does not yield the most efficient light collection in these long detectors. The replacement of the photomultiplier tubes with pin diodes along the detector length would yield a much more rugged detector assembly and improve the light collection. The latter will provide an improvement in the system imaging performance.

The rotating source beam collimator assembly on the x-ray generator provides for the side-to-side sweeping of the x-ray generator beam and for the relatively fast imaging capability of the XMIS. To cut down on cost, the collimator was made from PVC plastic sewer pipe and the beam slits were cut manually. The low cost belt assembly that provides for the collimator rotation had a tendency to slip and jitter if the tension was not precisely adjusted. These limitations led to artifacts in the images, some of which could be compensated for. A carefully machined source beam collimator made from aluminum and a good drive assembly would provide a significant improvement in the XMIS imaging performance.

The length of the collimated detector lead collimators has a very significant effect on the quality of the collimated detector images. The optimum length increases with the depth of burial of the object that is being imaged. The collimator lengths on the XMIS were fixed. To achieve the effect of a change in length of the collimators, the whole assembly was raised or lowered relative to the ground using the four hand-powered jacks attached to the system frame. This was extremely cumbersome and not very precise. Changes in collimator length of a centimeter are significant. Each of the detector collimators should have a small motor assembly that provides for fast, automatic changes in their length.

All of the above identified system modifications could be achieved within 12 months and the resulting improvement in image quality should reduce the required x-ray generator power level (750 watts for these first field tests) by at least a factor of two.

There is one other modification that could yield a significant improvement in system performance. While the rotating source collimator provides for rapid side-to-side scanning, incidence of the source beam on the ground at varying angles during the scan yields a varying spot size and varying spot velocity on the ground surface. These non-uniformities must be corrected for in the imaging process. A more effective arrangement would be to use a multi-cathode x-ray generator with a single rod anode tube. The cathodes would extend along the length of the tube. These cathodes do not have to be fired sequentially, but can be multiplexed and fired according to a preset order so as to obtain a series of beams to achieve the side-to-side scanning. In this way, a longer data collection time can be achieved for each cathode without suffering any interfering signal from a nearby cathode being fired quickly after. Work on a prototype seven-cathode x-ray generator has been done by Bio-Imaging Research, Inc. and development of multi-cathode generator for the XMIS system would take a year to two years. This will increase the speed with which the system can image, improve image quality and system reliability and further reduce the required x-ray generator power level. High resolution scanning of a 50 cm by 50 cm area which takes about a minute with the current XMIS should take about 20 s with a multi-cathode x-ray generator operating at a power level of around 300 watts.

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