Fusion of Acoustic/Seismic and Ground Penetrating Radar Sensors for Antitank Mine Detection

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ABSTRACT

Data fusion from two separate and orthogonal mine detection sensors developed independently by the University of Mississippi and Planning Systems Incorporated has been performed. The University of Mississippi's acoustic/seismic coupling detection is based on the measurement of ground surface vibration velocity by means of acoustic excitation and a laser Doppler vibrometer. Differences in absolute surface vibration velocity, caused by the presence of buried mines, are used to infer the presence of buried land mines. Planning Systems Incorporated uses ground-penetrating, synthetic-aperture radar (GPSAR) to detect subsurface electromagnetic anomalies. Detection with the GPSAR sensor is based on differences in the dielectric constant of the ground medium and that of a buried land mine. The spatial resolutions of the two measurements are similar and the two sensors measure completely different physical properties. Data from each system are described in detail and independent examples of performance are presented. A common geo-spatial grid is defined for both sensor systems given their respective resolving capability. Methods of simultaneous display are presented and situations in which the two systems are complementary are identified. This effort is sponsored by the U. S. Army Communications-Electronics Command Night Vision and Electronic Sensors Directorate.

I. INTRODUCTION

Recent struggles in foreign lands have highlighted the need for effective mine detection sensors. An effective sensor pinpoints the mine location with a very high probability of detection and a very low false alarm rate. The mines encountered today come in a plethora of sizes and materials and are buried at various depths, in various types of soil, and under various conditions. This confluence of variables is weighted against an ability to rely upon a single sensor. Most sensors have both strengths and limitations: conditions under which they are able to locate mines better than other sensors. Sensor fusion provides an opportunity to meld together two or more sensors to complement one another's strengths while compensating for weaknesses. The end result is a significantly higher probability of detection and lower false alarm rate, with obvious benefits to the warfighter. The trick is to identify sensors that are truly orthogonal, that exploit disparate phenomena to locate mines while producing similar data that can inform a single "mine/no mine" decision. The University of Mississippi and Planning Systems Incorporated (PSI) have independently developed two technologies that meet this criteria: acoustic-to-seismic coupling (A/S) and ground penetrating synthetic aperture radar (GPSAR).

Both technologies have proven to be highly successful in independently scored blind testing sponsored by the U. S. Army yet they exploit completely different physical phenomena to pinpoint mines. The University of Mississippi's A/S technology exploits the mine's resonance response to acoustic-to-seismic coupling of sound into the ground while PSI's GPSAR identifies differences in the dielectric properties between the ground and buried objects. However, the two systems produce data based on common geospatial coordinates making fusion at a pixel level possible.

The two systems complement one another admirably. At shallow burial depths, the GPSAR signature of the mine is difficult to separate from the ground return, yet this is where the A/S signature is strongest. At depths of six inches or greater the A/S signature becomes larger in extent and weaker in strength, yet the GPSAR has little trouble identifying the mine. In extremely moist soil the attenuation of the radar signal becomes large, but the A/S signal is minimally affected. The acoustic technique works in short grass but has problems with fallen leaves and is not expected to work in high grass, yet these conditions pose little problem for the GPSAR. A/S detection appears to work best against plastic mines due to their higher resonance, while GPSAR appears to work best against metal mines due to the large contrast in dielectric properties between soil and mine. The two sensors have comparable resolutions of a few centimeters, which allow fusion at the pixel level as well as other types of fusion. Along with infrared detectors, these sensors are almost the only ones with even theoretical detection capability at ranges beyond ten meters. While at present the A/S technique is slow, there is no physics-based reason to prevent either sensor from operating at speeds required to meet military requirements.

II. THE A/S SYSTEM

The University of Mississippi's A/S detection system locates mines by insonifying the ground and measuring its vibrational velocity in a two-dimensional spatial ground-velocity field. Loudspeakers broadcast pseudo-random noise in a frequency range from approximately 80-400 Hz, a range based on the natural frequencies of buried landmines. The acoustic energy enters the porous ground and is coupled into seismic motion of the solid matrix of the soil. This energy causes the compliant top of the mine to resonate and the energy is returned to the surface where it causes increased vibrational velocity. The area of increased vibrational velocity is approximately the same size and shape of the mine. Because mines resonate while most natural objects buried in the soil do not, this technology is relatively insensitive to clutter. The ground velocity is measured using a laser Doppler vibrometer, a non-contact sensor.

The general current setup of the University of Mississippi A/S apparatus is shown in Figure 1. The laser beam moves from point to point on the ground and scans a grid. The grid spacing is set to one third or less of the diameter of the expected mine and is never greater than 10 cm. Thus the mine is spatially oversampled. The surface vibrations are measured at various frequencies over a selected band, which is within the frequency range of 20 to 400 Hz.

The signature of a mine is a cluster of grid points representing increased surface velocities that roughly form a circle. This detection of multiple adjacent points is very robust since recognition of the presence of a mine is not based on single point detection. Down to a burial depth of up to six inches to the top of an antitank mine, the signature is still quite clear. The strength of the signature is sensitive to the resonance characteristics of the mine and is strongest at the natural frequency of the mine. Typical optimum frequencies are 175 Hz for antitank mines and 300-400 Hz for antipersonnel mines. Additional details about the A/S detection system are given in Reference [2].

Currently, identification of a mine is based on an area of increased velocity that is the correct size and shape for a mine and that remains constant when viewed in multiple frequency bands. The U. S. Army Communications-Electronics Command Night Vision and Electronic Sensors Directorate is currently sponsoring a separate program to devise automatic target recognition algorithms to improve mine recognition resulting in a higher probability of detection.

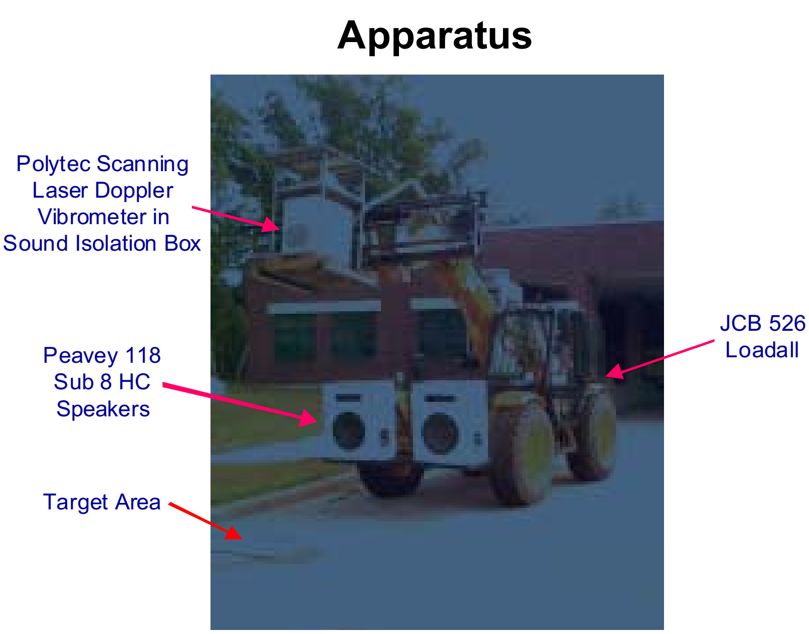

Figure 1. A/S detection system with a laser Doppler vibrometer.

III. THE GPSAR SYSTEM

The ground penetrating synthetic aperture radar (GPSAR) developed by PSI finds mines by producing a detailed spatial map of changes in the dielectric reflective properties of the ground as a function of depth. A photograph of the GPSAR system as configured in November 1999 is shown in Figure 2.

The radar electronics of the GPSAR system operates the antenna banks shown in Figure 2, each of which contains seven transmitter and seven receiver antennas. Each antenna bank has a dedicated radar module that operates over the frequency band 500 to 1800 MHz. A radio frequency (RF) switch bank is used in conjunction with the antenna bank to acquire data from equally-spaced locations orthogonal to direction of the radar advance for each of the two antenna banks. Along-track resolution is obtained via forward motion of the system with data acquisition at prescribed intervals initiated by a mounted optical encoder. The resulting two-dimensional data grids are processed using synthetic aperture, nearfield beamforming to produce volumetric images of buried objects. Spatial filtering techniques are used to enhance the presence of the small dielectric anomalies associated with buried plastic mines.

The sweep width of the GPSAR system is approximately one meter. The back and front antenna banks each record data over 13 equally spaced points, each 2.76 inches apart. These two antenna banks are offset by 1.38 inches in the cross-track sense. Thus, the combined cross track spatial sampling of the system is 1.38 inches. Log spiral antennas are used. The transmitter and receiver antennas are wound in opposite directions in order to minimize direct coupling effects. Due to the directional nature of these antennas, the system is not plagued by hyperbolic-shaped image anomalies common to other ground penetrating radars. Under normal operating conditions data is recorded at 66 equally spaced frequencies over the 500-1800 MHz band. The depth resolution of the system is approximately 3 inches. The heights of the antenna arrays above the ground are electrically adjustable, thereby facilitating data collection at different antenna heights. In its present configuration, the GPSAR can move forward at a speed of about 1000 ft per hour, depending upon frequency sampling interval, total bandwidth and along-track sampling increment. By using additional radar modules and faster digital circuits, significant increases in operational speeds of advance for the system can be achieved.

Figure 2. GPSAR in action. Major system components visible in this photograph include the front and rear antenna banks and the onboard laptop computer. The radio frequency switches that switch a single-channel, stepped-frequency radar across each antenna pair are located directly above the antenna banks. The radar electronics are located between the front wheels of the radar cart and the battery is located between the rear wheels.

IV. SIMILARITIES IN DATA FORMATS

The University of Mississippi's A/S sensor and the PSI GPSAR both record data in three dimensions, two of which are spatial (cross track/along track denoted by *xy*). The GPSAR records an *xy* spatial map of the ground's complex frequency response. This frequency domain data is converted to a time/depth representation using Fourier transforms or their analogs. Similarly, the A/S sensor records frequency-dependent velocity data that is resolved through use of a Fourier transform at each *xy* coordinate. Since both systems collect similar types of data across identical *xy* coordinates, sensor fusion at the pixel level is feasible.

Figure 3 shows sample images produced by both systems. The target in question is an M19 plastic mine buried at 5 inches depth on Calibration Lane 13. These images are presented on a color-coded intensity scale. The A/S image (3a) covers a one square meter area and is shown in a frequency band of 120-130 Hz. The mine is identified by a high velocity circular shape approximately 12 inches in diameter near the center of the image.

GPSAR images of this same mine are shown in Figure 3b. The upper portion of the figure shows the *xy* display and the lower portion of Figure 3b shows the corresponding depth slice image. The GPSAR imaged a volume that was one-meter by one and one-half meter square and 12 inches in depth. Since volumetric images are difficult to display graphically, the maximum intensity is mapped onto the *xy* coordinates and the maximum intensity is mapped onto along-track/depth coordinates to produce the side view display. The mine is clearly resolved in depth by the GPSAR. This capability to detect the depth of targets is extremely important in the GPSAR detection process.

Of the two images produced by the GPSAR, the *xy* display is obviously most similar to the A/S image. Cropping the GPSAR image so that it corresponds to the same *xy* coordinates as the A/S image allows direct comparison of the two system's resolution. In producing these figures, there has been no attempt to exactly align the "hot" spots produced by the mine.

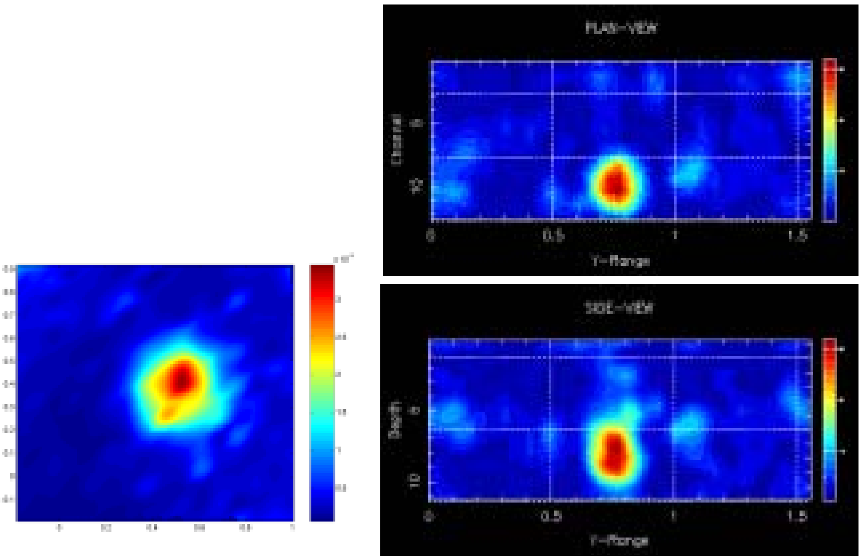

Figure 3. a. Image of an M19 plastic mine buried at 5 inches in Lane 13 produced with the A/S system. **b**. Images of the same M19 plastic mine buried at 5 inches on the Lane 13 produced with the GPSAR system.

V. SIMILARITIES IN PERFORMANCE MEASUREMENTS

After identifying mine technologies that use different physical phenomena to locate landmines and after ascertaining that similar data may be produced to permit fusion, the next step is to ensure they perform well. The metrics for effective mine detection are clear: a high probability of detection, a low false alarm rate, and a low circular error probable (CEP) in pinpointing the mine location. These two technologies were subjected to similar U. S. Army-sponsored testing in April and November of 1999. Data were collected by each system over all the mines in Calibration Lanes 13 and 14 and at other calibration sites as well. Additionally, both systems were subjected to blind testing on sites located in Lanes 2, 3, 4 and 5.

The two calibration lanes are 50 m long and 3 m wide but are constructed of different materials: Lane 13 is dirt while Lane 14 is gravel. Lane 13 contains 11 buried mines and Lane 14 contains 10 buried mines. Details about the individual mines buried in these lanes are shown in table 1.

During calibration testing in April and November of 1999, the A/S system successfully located all 21 mines in Lanes 13 and 14. During this same time period, the GPSAR imaged 10 of 11 mines on Lane 13 and 9 of 10 mines on Lane 14. The difficult mines for the GPSAR to image were a SIM25 at 2-inch depth on Lane 13 and a SIM30 at 2-inch depth on Lane 14. The SIM25 and SIM30 are mine simulants rather than actual mines and have proven to be difficult targets for the GPSAR to detect in some circumstances. It is interesting to note that the GPSAR was able to image an EM12 at 1-inch depth on Lane 13 and an EM12 at 1-inch depth on Lane 14 since the EM12 is the predecessor of the SIM30.

To demonstrate the similarity of data collected in these tests, Figure 4 pairs A/S and GPSAR images for two mines located in Lane 13. A similar comparison for Lane 14 mines is presented in Figure 5. Each image is shown full scale; no effort has been made to suppress background clutter. Also, no effort has been made to align the mine in the exact same fashion, so the position of the mine in the images is not always the same. Nevertheless, the images clearly show the similarity of data between the two systems. In almost all cases, the size of the hot spots is similar in spatial extent.

In April of 1999 the A/S system was subjected to independently-scored blind testing in which data was collected over 19 mines, 31 blank spots and 9 additional spots known to produce false alarms in multiple other ground penetrating radar systems [3]. In November of 1999, the GPSAR system was also subjected to blind testing in which data was collected over 17 mines and 31 blank spots [4]. For each spot, the area imaged was one square meter. Each team examined the real-time images of the collected data and decided whether mines were present on the spot.

In these blind tests, the A/S team scored a P_d of 95 percent with one false alarm for a P_{fa} of $0.03/m^2$ including no false alarms over the 9 ground penetrating radar clutter spots. Positional accuracy was within 5 cm. The GPSAR team scored a P_d of 76 percent with one false alarm for a P_{fa} of $0.03/m^2$. The false alarm for each system occurred at the same location, which corresponds to the normal location of a surface mine.

Figure 6 shows images of two mines from the April/November 1999 blind testing in which both the A/S and GPSAR systems correctly identified the presence of a mine. The mines shown in the figure are an EM12 at 1-inch depth and a VS22 at 2-inch depth. These are both plastic mines at shallow depths and both systems imaged them clearly and accurately. Again, the A/S and GPSAR images are presented full range with no attempt to eliminate clutter. Conversely, Figure 7 shows images from two sites where the A/S and GPSAR systems both correctly declared that no mine was present. Figures 6 and 7 show that clutter signals for the A/S system are generally lower than for the GPSAR system.

Images from the four sites in the blind test in which the GPSAR incorrectly declared no mine was present are shown in Figure 8. In each case the target missed by the GPSAR was a plastic mine. The A/S system correctly identified the presence of mines at three of these sites (upper left, upper right and lower left of figure 8). Both systems failed to identify the presence of the TMA4 at 6-inch depth in Site 190. In post-processing, the GPSAR team correctly identified the presence of this mine.

Figure 9 shows images from two of the nine places that were known to produce false alarms in multiple other ground penetrating radar systems. The GPSAR was not subjected to blind testing at these sites; however data was recorded at these nine sites with an earlier version of the GPSAR system in April of 1999. An examination of this data by PSI indicates that these nine sites would have produced four GPSAR false alarms. Data from two of these four sites is compared to the corresponding A/S data in Figure 9. As previously mentioned, the A/S system produced no false alarms at these nine sites.

Figure 10 shows images produced by the A/S and GPSAR systems of two deeply buried mines located in an off-road lane. The left side of the figure shows the return from an M21 mine buried at 6 inches. The right side of the figure shows the return from an M21 mine buried at 8 inches. The A/S system has difficulty in detecting the deeply buried mines. The mine at 6 inches depth is not visible at all while the mine at 8 inches depth is only faintly visible. To demonstrate the complementary strength of the GPSAR system, it readily detects the two deeply buried metal mines.

Lane	Mine	Type	Depth	Lane	Mine	Type	Depth
13	TM62M	metal	6"	14	EM12	plastic	1"
13	VS22	plastic	1"	14	M21	metal	2"
13	VS16	plastic	6"	14	TMA4	plastic	6"
13	TMA4	plastic	2"	14	SIM30	plastic	2"
13	SIM25	plastic	2"	14	VS16	plastic	3"
13	M19	plastic	5"	14	TM62P	plastic	1"
13	EM12	plastic	1"	14	VS22	plastic	3"
13	TM62P	plastic	2"	14	M15	metal	6"
13	VS16	plastic	1"	14	M15	metal	4"
13	M21	metal	1"	14	VS22	plastic	
13	M15	metal	3"				

Table 1. Summary of mines located in Lanes 13 and 14.

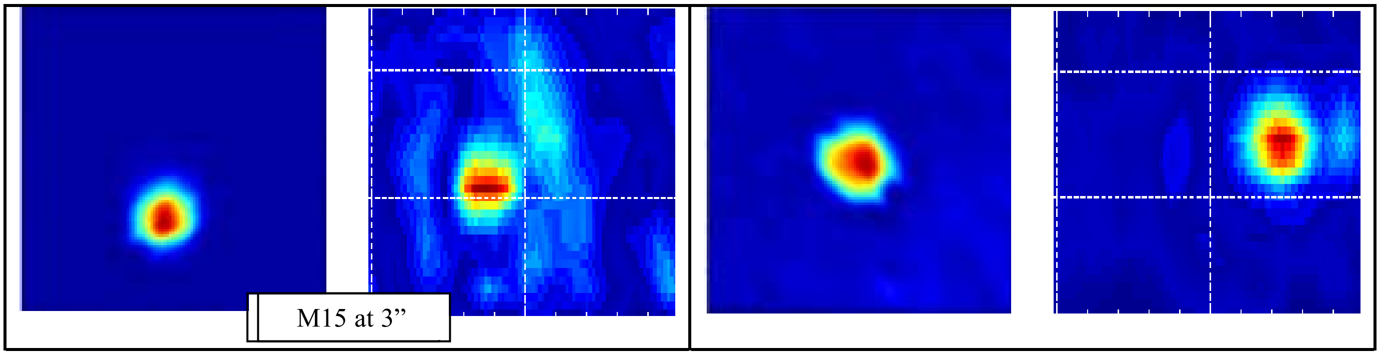

Figure 4. A/S and GPSAR mine images from Calibration Lane 13. VS1.6 at 1-inch depth on left. M15 at 3-inch depth on right. For each image pair, the A/S image is shown on the left and the GPSAR image is shown on the right. In each case the imaged area is one meter by one meter.

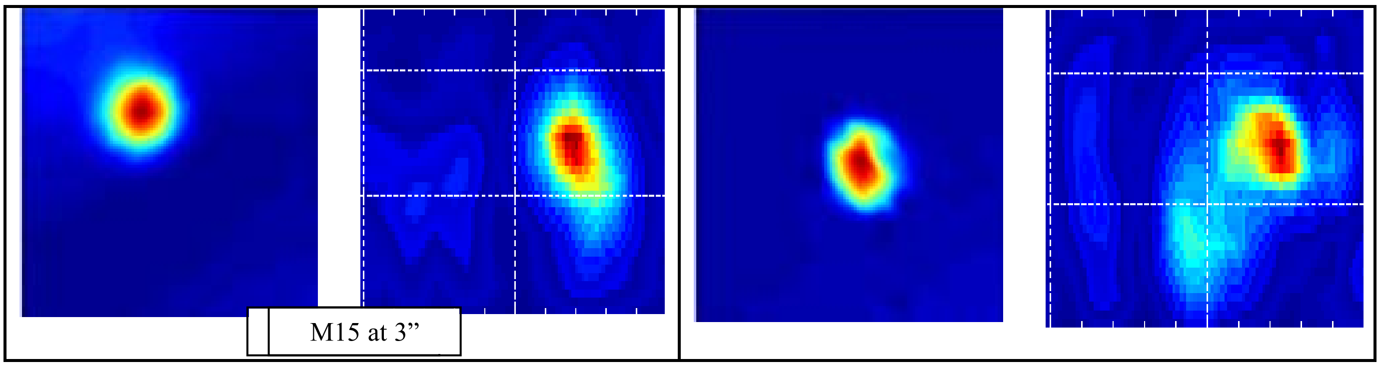

Figure 5. A/S and GPSAR mine images from Calibration Lane 14. VS2.2 at 4-inch depth on left. M15 at 3-inch depth on right. For each image pair, the A/S image is shown on the left and the GPSAR image is shown on the right. In each case the imaged area is one meter by one meter.

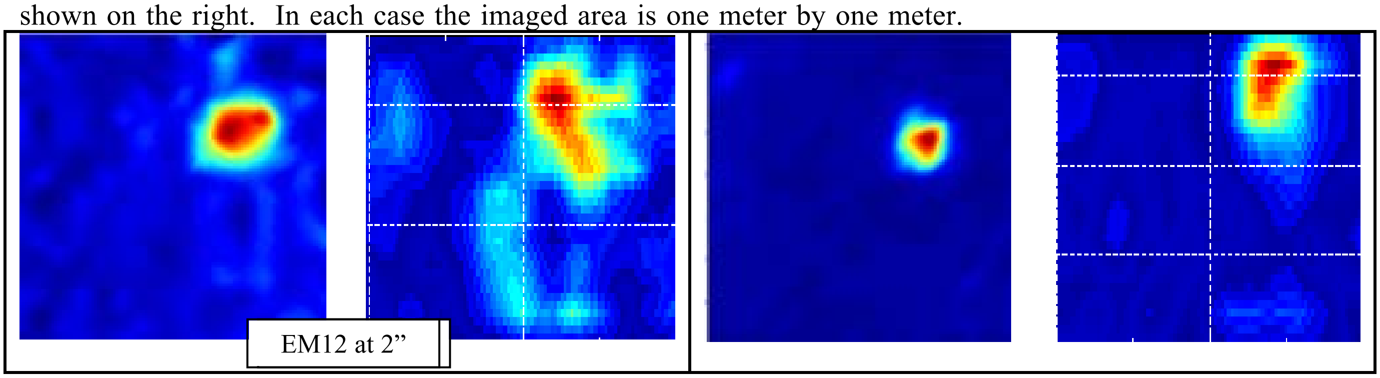

Figure 6. Images of mines in the April/November blind testing in which both the A/S and GPSAR systems correctly identified the presence of a mine. Site 219, on left, EM12 at 2-inch depth. Site 229, on right, VS22 at 2-inch depth. For each image pair, the A/S image is shown on the left and the GPSAR image is shown on the right. In each case the imaged area is one meter by one-meter square.

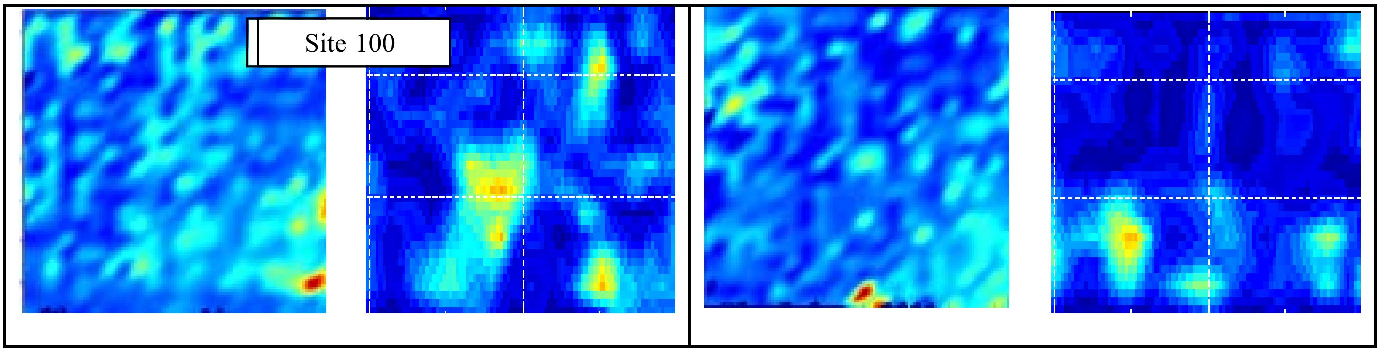

Figure 7. Images from sites in the April/November blind testing in which both the A/S and GPSAR systems correctly declared no mine was present. Site 70, on left. Site 100, on right. For each image pair, the A/S image is shown on the left and the GPSAR image is shown on the right. In each case the imaged area is one meter by one meter.

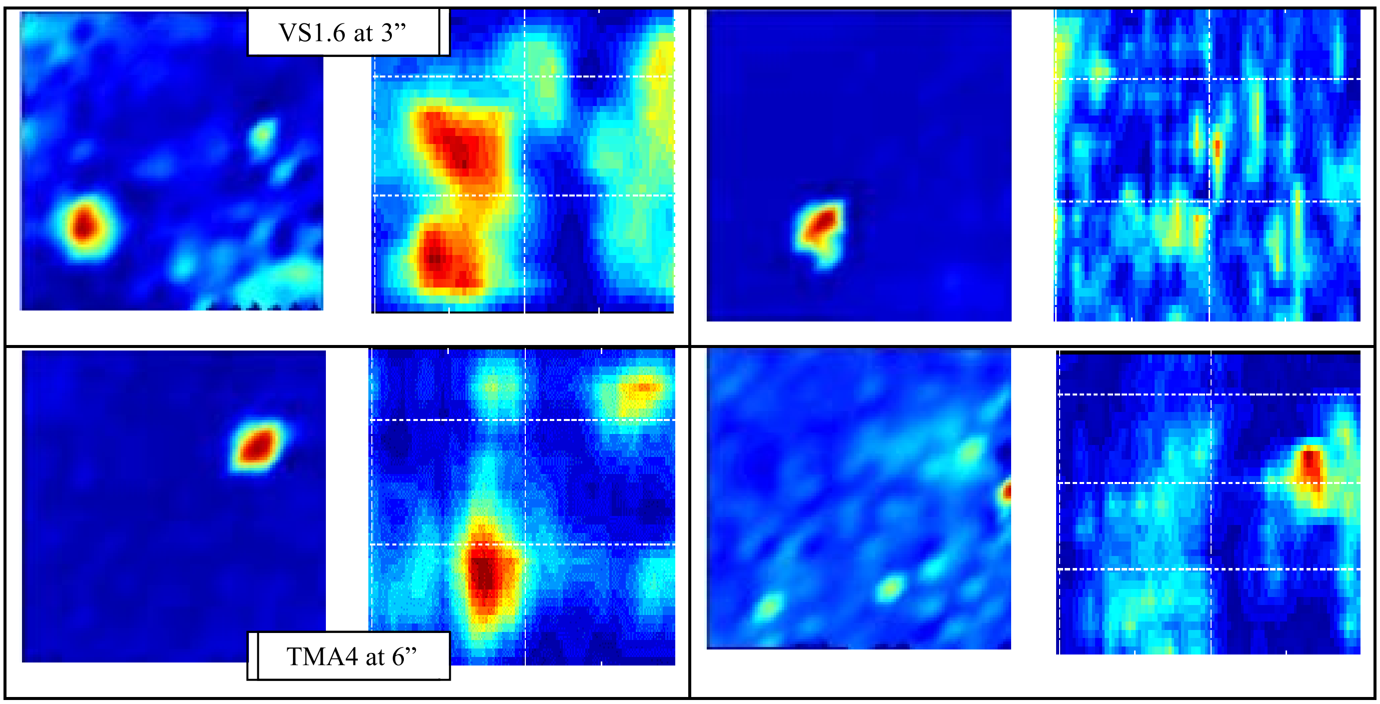

Figure 8. Images from sites in the April/November blind test where the GPSAR incorrectly declared no mine present. Site 90, upper left, VS1.6 at 3". Site 125, upper right, VS2.2 at 1". Site 115, lower left, EM12 at 1". Site 190, lower right, TMA4 at 6". The A/S system correctly identified the presence of mines at sites 90, 125 and 115 but missed at 190. In a post-processing mode the GPSAR correctly called mines at sites 115 and 190. For each image pair, the acoustic seismic image is shown on the left and the GPSAR image is shown on the right. In each case the imaged area is one meter by one meter.

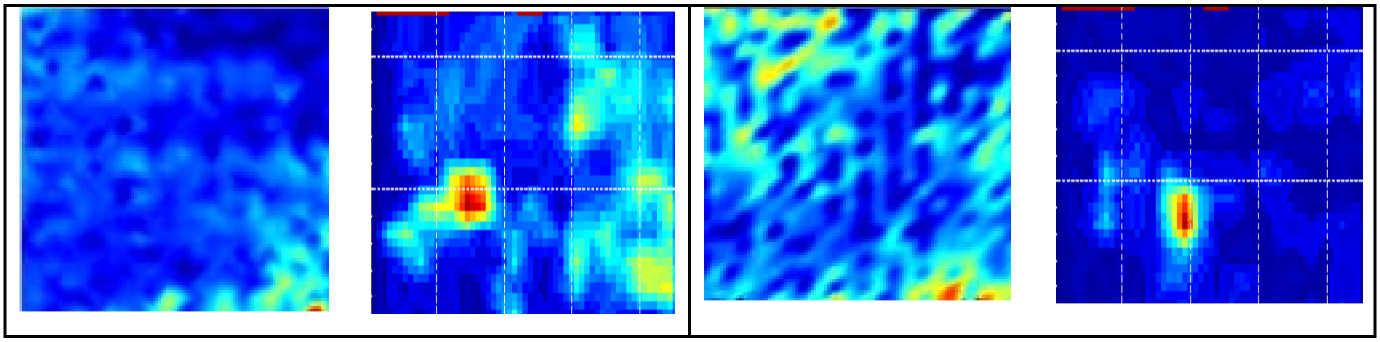

Figure 9. Images from two known high GPSAR false alarm spots in the April blind test where the A/S system correctly declared no mine was present. The A/S image is shown on the left and the GPSAR image is shown on the right. In each case the imaged area is one meter by one meter.

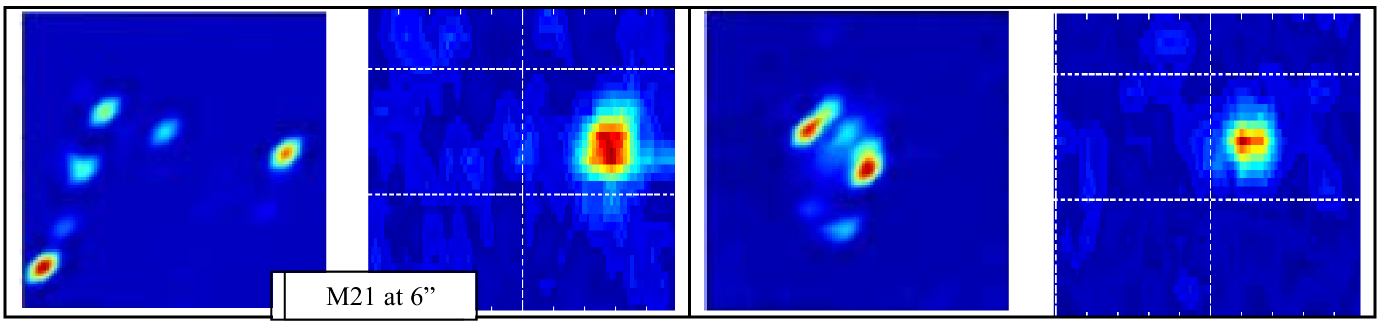

Figure 10. Images of two deeply buried mines in an off-road lane. The left side of the figure shows the return from an M21 mine buried at 6 inches. The right side of the figure shows the return from an M21 mine buried at 8 inches. The A/S image is shown on the left and the GPSAR image is shown on the right. The imaged area is one meter by one meter.

VI. CONCLUSIONS

The A/S technology developed by the University of Mississippi and the GPSAR developed by PSI appear to meet the criteria for successful fusion of mine detection sensors. They exploit disparate phenomena, complement each other’s strengths and weaknesses, and produce similar data in a similar format. Both systems have proven performance, high probabilities of detection with almost identically low false alarm rates, demonstrated through independently-scored blind testing. The success in meeting these criteria indicates that fusion of these two technologies can produce an effective mine detection system. Based on this promise, the University of Mississippi and PSI plan to fuse these two technologies into a single mine detection system in the near future.

VII. ACKOWLEDGEMENTS

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VIII. REFERENCES

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