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Energy Focusing Ground Penetrating Radar (EFGPR) Overview

1. EFGPR Theory Of Operation

Why EFGPR is Different from Other GPR Mine Detection Technologies

Many different approaches to mine detection have been lumped under the acronym "GPR." Conventional bistatic impulse radar has been employed as far back as the Korean war to detect subsurface tunnels. Bistatic impulse radar emits a short burst of energy which incorporates a broad range of frequencies on a single transmit antenna. Some portion of the radiated energy is back scattered by objects having a different dielectric constant and is collected by a single receive antenna. Other radar approaches include generating continuous frequencies in a narrow band or bands, either by discrete steps, continuous sweeping, or "chirping" (a short burst of swept frequencies). Synthetic aperture radar (SAR) utilizes multiple antenna locations to improve resolution of the resulting image, essentially creating a larger antenna from multiple smaller antennas. This can also be accomplished by using a single antenna at multiple locations over successive times, by using multiple antennas, or by a combination of the two. Generally, the collected data then must be post-processed to form either a time or frequency domain representation of the scanned area.

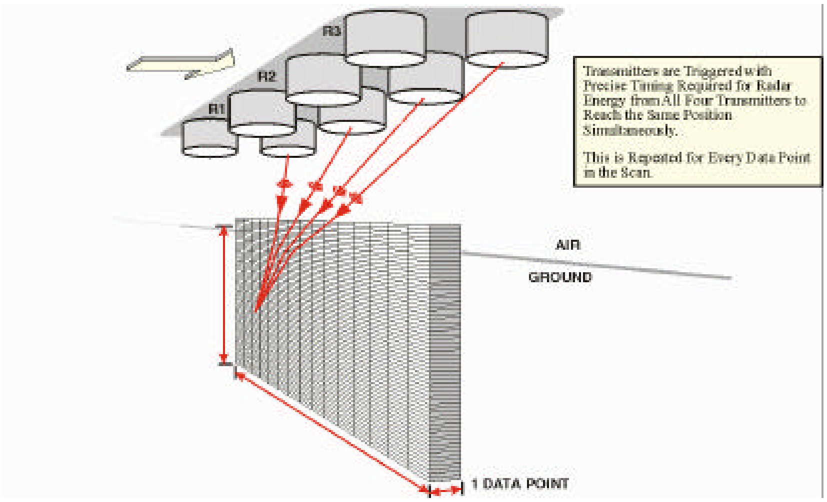
In contrast, GEO-CENTERS' Energy Focusing Ground Penetration Radar (EFGPR) incorporates both bistatic impulse radar and synthetic aperture (SAR) principles by using a two-dimensional array of precisely timed transmitters and receivers to actively image the area under the array. This provides the advantages of multiple transmitters to illuminate the scanned area with broadband energy, multiple receivers to detect back-scattered energy, and provides additional clutter rejection through time-domain synchronization of multiple impulse radars. By independently controlling the firing and gating of each transmitter and receiver, the system focuses radar energy to a point, then moves that point to scan the area under the array. The data collected form a subsurface time domain image of the back-scattered energy without requiring processing-intensive translation from the frequency domain. This image is analyzed in real time using multiple, independent target recognition algorithms in parallel. Outputs from the target recognition are fused in real-time to declare mine targets and their location.

Unlike many ground penetrating radars which were adapted from general geophysical survey instruments, GEO-CENTERS' EFGPR was designed specifically for the detection of landmines. The system is unique in its ability to:

- Focus in hardware
- Acquire three-dimensional data
- Be configured for a wide variety of environments
- Have ATR algorithms that perform intra-sensor data fusion

Focusing in Hardware

The way in which GEO-CENTERS' EFGPR uses its controlling electronics to trigger multiple transmitters and receivers to focus is unique and patented. The EFGPR operates by firing groups of four independent transmitters and sampling groups of four independent receivers for each voxel location. For any given voxel, the timing of the impulse from each of the four antennas is precisely controlled so that transmitted energy is coincident in time and thus is focused at the desired voxel location (see Figure 1). Likewise, the sampling of each receive antenna is independently timed to be coincident with the transit time of the scattered energy return, focusing the receivers on the desired voxel. On-board software models the time-of-flight through the air/ground media, calculates the timing settings required to achieve this precise alignment, and uploads these “focus tables” to the controlling electronics. This method of focusing multiple transmitters and receivers both enhances the signal return from a given location and reduces the signal level from other areas not being focused upon (incoherence in scattered returns from other voxels causes them to be “out of focus”). Changing the relative timing between the four antennas allows the focus to be scanned left to right, generating voxel data in the cross-track dimension. As the scanning process is entirely controlled by uploaded focus tables, the number and spacing of sampled voxels is completely programmable. Typically, the cross track spacing between voxels is 2” (5 cm), and the depth increment is approximately ¼” (0.6 cm).



Transmitters are Triggered with Precise Timing Required for Radar Energy from All Four Transmitters to Reach the Same Position Simultaneously.

This is Repeated for Every Data Point in the Scan.

Figure 1. The Energy Focusing concept using groups of four transmitters and receivers.

Acquisition of Three Dimensional Data

Most ground penetrating radar arrays require extensive signal processing to localize and identify targets. In contrast, GEO-CENTERS’ EFGPR is designed to raster-scan the ground, focusing the combined energy from multiple transmitters on each voxel and only sampling the receivers when the scattered return from that voxel is expected. This obviates the need to collect and analyze massive volumes of data to isolate the scattered return from an object. Successive raster scans are averaged over a constant interval of down track motion (typically over every two inches of forward travel), resulting in high-precision high signal-to-noise spatially normalized radar image. This continuous down track scanning generates a complete three-dimensional subsurface radar image of the traversed area, as illustrated in Figure 2. As the output of the EFGPR system is already image data, no additional processing steps are required to produce a three dimensional volume of image data. The resulting image data can be analyzed using standard image processing techniques for enhancement and target detection. GEO-CENTERS’ Automated Target Recognition (ATR) algorithms function on these three dimensional data as the data are collected, and provide a confidence mapped plan view output as well as target reports in real time.

A Programmable and Configurable Radar

Focusing of the array is controlled through timing parameters passed to each independent antenna controller in the form of focus tables. Focus tables are generated by the host computer, and each module receives the portion of the table that it is responsible for executing. A focus table essentially defines a loop that each module repeatedly executes in which one pass through the loop results in a complete scan. The geometry of the scan is fully programmable, which allows variations in the size of the array to be easily accommodated. GEO-CENTERS routinely operates the EFGPR sensor with one, two, or three modules of five antennas each as required. The ability to reprogram operation of the array also offers tremendous potential for development of enhanced capabilities such as higher resolution scanning, increasing data throughput by interleaved operation of sub-arrays, real-time measurement of soil parameters, or "on-the-fly" changes to the radar scan.

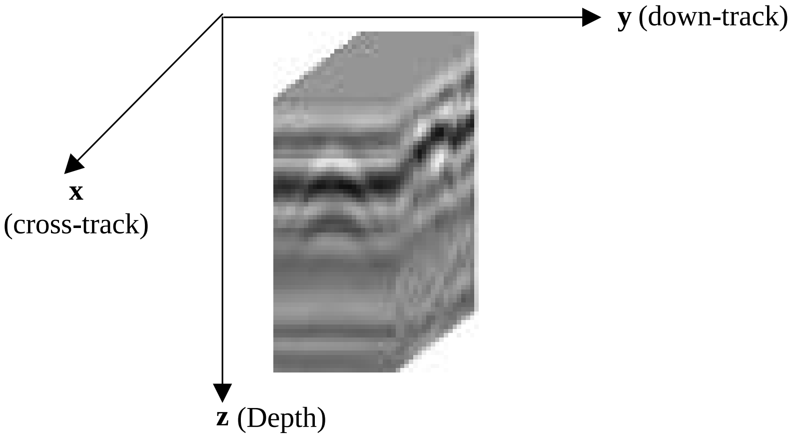


Figure 2. Three-dimensional antitank mine signature from the Model 301 EFGPR.

Typical system operation starts a scan at one inch above the ground surface and proceeds to a depth of about eight inches below the surface and across the width of the array. Scans are averaged over two-inch intervals of down-track movement. Current EFGPR systems incorporate a minimum of 4 and a maximum of 16 elements; three 5 element arrays provide a physical cross-track width of up to 3.5 meters (3 m nominal). The geometry and the use of successive groups of 4 antennas to focus at a single point is illustrated in Figure 3. Height above ground(standoff) for the system is nominally 15 inches (38 cm), and spacing between antenna array elements is 10 inches (25 cm). For a 3.5 meter width (3 arrays), this results in a scan geometry of 70 voxels in the cross-track dimension and 32 voxels in the range (depth) dimension where the voxel dimensions are two inches by two inches (five by five cm) of surface area and approximately one-quarter inch (0.7cm) in depth. Transmitters are located in a row at the front of the array and receivers in a row at the rear of the array, separated by a distance of ten inches (25 cm). These were the nominal values used at the US Army Vehicular Mounted Mine Detection (VMMD) Advanced Technology Demonstration (ATD), although actual scan geometry, vertical start and stop limits, and data acquisition characteristics of the EFGPR are completely programmable.

The nominal sample rate of the EFGPR is 0.8 megasample/sec, which allows approximately nine complete scans of (70 by 32 voxels) to be acquired over a two-inch down track distance at 6 kph. This scan data is spatially normalized to the two-inch encoder interval so that a new scan is submitted to the host computer every two inches of down-track motion. The host computer buffers this data for use by its ATR routines, which provide target identification messages to the Integration processor (IP) computer.

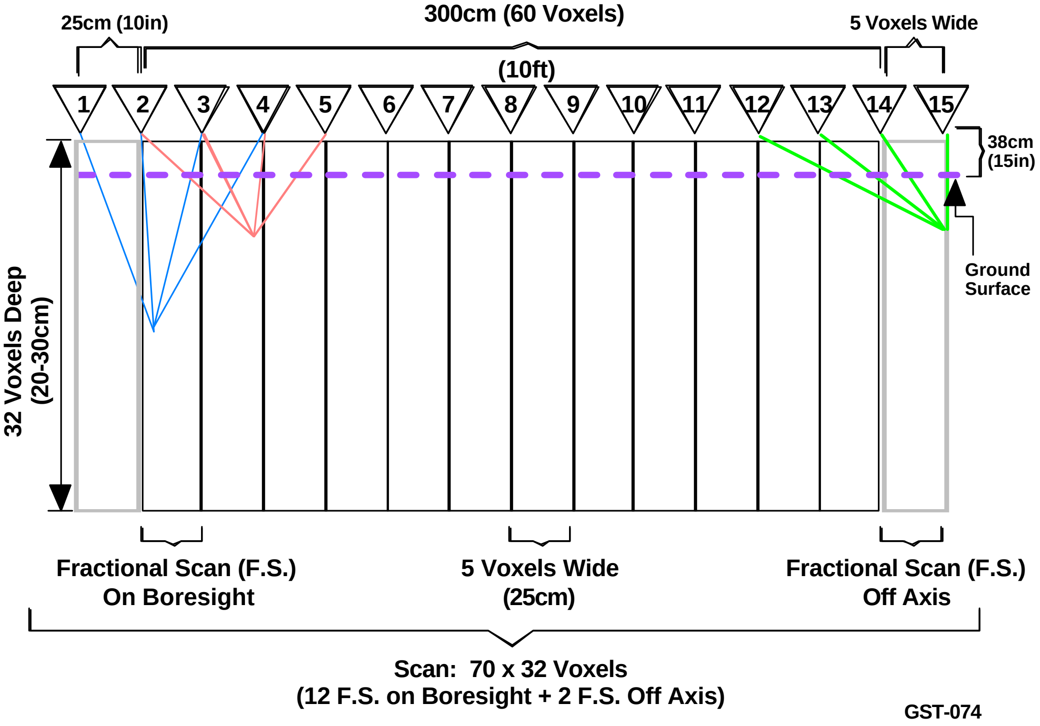


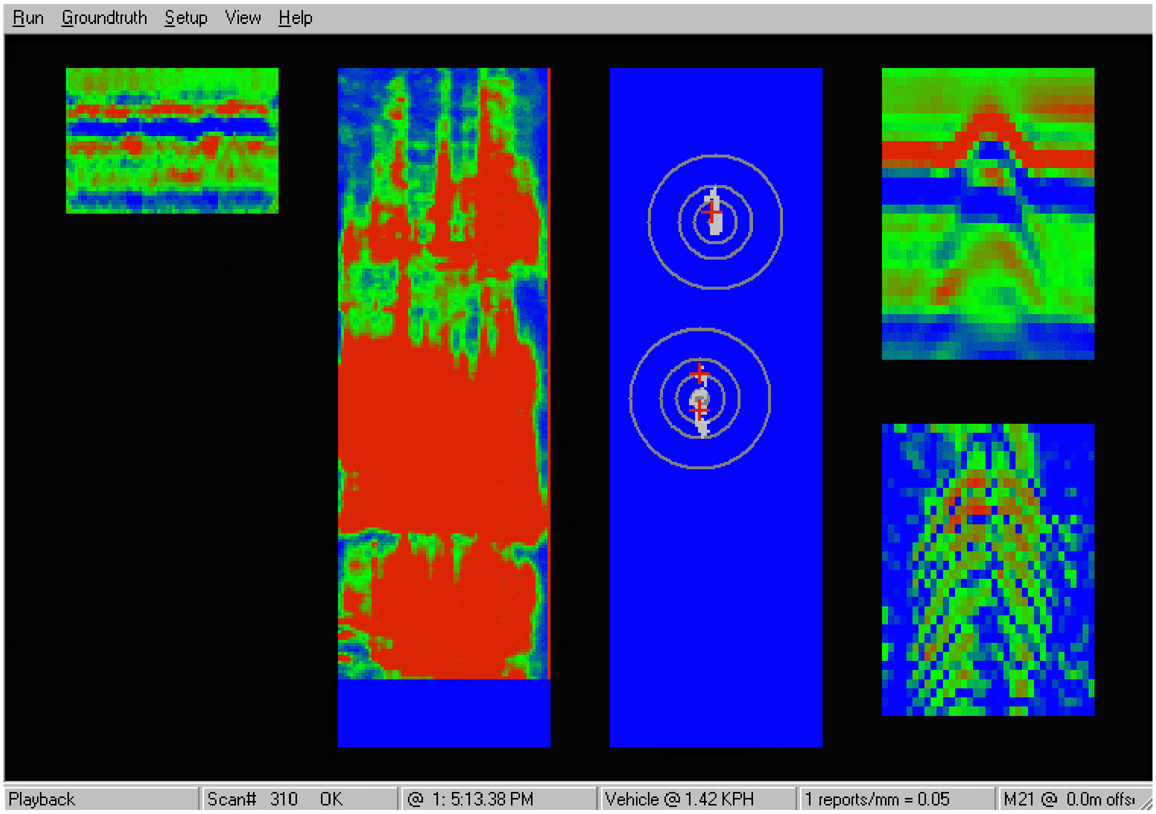
Figure 3: Focusing by Changing the Group of Four Transmitters and Receivers Across the Array

The programmability of the EFGPR allows the radar to be tailored to the application and environment. Data density, depth of scanning, height above ground, and focus for wet or dry soil all are easily set through the system control software, operating under Microsoft Windows NT 4.0. In addition to controlling radar operation and data storage / playback, this software provides functionality for subsystem test, generation of focus tables, automated timing alignment of transmitters and receivers, as well as access to control settings for the real-time ATR. The EFGPR control software also accommodates connection to global positioning systems in RTK mode (2 cm accuracy), allowing target reports to incorporate Universal Transverse Mercator (UTM) coordinates. Operation of the system can be performed either through an expert mode graphical user interface (GUI) or a deminer mode GUI that utilizes preset operating configurations.

ATR Algorithms that Perform Intra-Sensor Fusion

The ATR algorithms demonstrated at the US Army's Vehicular Mounted Mine Detection (VMMD) System Advanced Technology Demonstration (ATD) utilize a fuzzy logic-based approach where features are extracted at each point in space and examined for mine and clutter characteristics. If a point is more clutter-like, it is ignored; if it is more mine-like, a confidence value is generated and assigned to that location. A confidence plan view is generated, and a blob detector runs on the confidence plan view to declare mine-like targets (see Figure 4). GEO-CENTERS has also developed intra-sensor information fusion methodologies. With this approach multiple ATR and feature extraction algorithms are run in parallel. The outputs from these algorithms are fed to a fuzzy inference system which outputs a system wide confidence. This intra-sensor fusion approach has proven to be very successful at holding probability of detection high while reducing false alarms. Note that GEO-CENTERS ATR approach of multiple algorithms extracting features and feeding a fuzzy inference system is equally applicable to inter-sensor fusion and multi-sensor systems.

The down-track energy (depth plot) in Figure 4 provides the best graphical representation of the raw EFGPR signal that results from buried and surface laid landmines. As can be seen in the upper right of Figure 4, a mine signature consists of a number of “hyperbolic” radar returns. This is the signature that the down track feature extraction algorithm is looking for. To enhance the contrast of this signature, the program creates a down track gradient data representation. In addition, a feature is extracted from the cross-track energy distribution. A gradient representation of these data is also created.



Playback | Scan# 310 OK | @ 1: 5:13.38 PM | Vehicle @ 1.42 KPH | 1 reports/mm = 0.05 | M21 @ 0.0m offs

Figure 4. The display of the 301 control (host) computer. The upper left image is the raw scan (cross track and into the ground). The next two images are the energy plan view (cross track and down track) and the confidence plan view with mine ground truth (concentric circles) and ATR output (red crosses). The images on the right are the raw and contrast-enhanced hyperbolic signatures detected by the ATR. The success of the ATR is apparent from its ability to correctly extract the ATR signatures from the cluttered background depicted in the energy plan view.

The ATR primarily operates on the gradient data. As new scan data are collected every two inches of forward advance, a three-dimensional representation of gradient data is created. A three dimensional template, defined by up to eleven down-track and depth pixel locations and up to two cross-track locations at a given depth is used to define specific locations in the three dimensional gradient data from which gradient values are extracted. The gradient values at these eleven locations become the feature set for the pixel that is located in the middle of the template. Using pre-defined target prototypes and clutter prototypes for features, fuzzy distance measurements from the data to each of these prototypes are calculated, and the distances from the data to the these prototypes are used to calculate a mine confidence value for the center pixel in the template. This process is repeated for each pixel that makes up the center scan in the volume of gradient data, thereby creating a cross-track by depth confidence representation. Once this operation is completed, a new scan is moved into the volume, the oldest scan is removed, and the process is repeated on the new center scan. This overall process creates a three dimensional representation of mine confidence as the EFGPR moves down track.

In addition to the ATR processing discussed above, for every pixel that is represented by a non-zero mine confidence value, two other features are extracted from the data. These are the number of hyperbolas associated with the radar returns, and a transitional feature value. The fact that there are multiple hyperbolic radar returns from a given target is evident in the down-track energy and down-track gradient representations. A feature representing the number of hyperbolic returns is generated from the radar data. The transitional feature value is the result of a second ATR that operates on the data. This ATR analyzes the spatial energy distribution of the first significant radar return (from the portion of the scan nearest the ground) and calculates a confidence value from this information. In the system as deployed at the ATD, the transitional feature value and the number of hyperbolas were used as “switches” (e.g. if the specified level was not met or exceeded, the confidence value associated with that pixel was set to zero).

The Energy Plan View is provided mainly for historical reasons and provides a two dimensional energy representation of the sum of the squares of the radar returns from the individual columns of the scan data. From here, track inhomogeneity is clearly evident, and the need for the more advanced confidence-based ATR is clearly demonstrated.

The Confidence Plan View is created by bringing the maximum level of confidence as a function of depth to the surface. This creates a two dimensional representation of the area surveyed based on the complete three-dimensional confidence image of the subsurface. As the data that were used to generate this figure are from a calibration lane where ground truth is known, both the mine’s location and a 1 meter halo surrounding the mine are also represented in the confidence plan view. A blob detector operates on the confidence plan view, and the crosshair on the figure shows the detection location from the ATR in the confidence plan view. Down-track and cross-track target locations can then be output as data or further processed with GPS data to determine target location in real world coordinates.

2. Implementations for Landmine Detection

EFGPR History

GEO-CENTERS has been involved in the development and use of GPR systems since the early 1980’s, first as general geophysical field instrumentation, then more specifically for ordnance and land mine detection. GEO-CENTERS first developed a focusing array of time domain radars in the late 1980’s, and through the course of both internal and US Government funding over the last decade, has developed the approach from concept to a field deployable system. A patent on the focusing approach was granted to GEO-CENTERS in 1995. Table 1 below provides a brief history of EFGPR evolution through a comparison of the basic system descriptions since 1990.

Table 1. Development History of GEO-CENTERS' Energy Focusing Ground Penetrating Radar for Landmine Detection

	Concept Demo	Model 101 "CMINE"	Model 101 "FAR"	Model 201 "ICCFAR"	Model 301 (301B)	HD test (301D)	Model 400 Series
Circa Year	1990	1992	1995	1996	1999	2000	2001
Radar Array Type	Time Domain Impulse	Time Domain Impulse	Time Domain Impulse	Time Domain Impulse	Time Domain Impulse	Time Domain Impulse	Time Domain Impulse
Focusing Method	Fixed (cable) Delays	Programmable Delays	Programmable Delays	Programmable Delays	Programmable Delays	Programmable Delays	Programmable Delays
Scan Geometry (cross track x depth during testing)	Single point	16 x 64 fixed	16 x 64 fixed	16 x 64 fixed	SW config'd (typ 20 x 64 per m)	SW config'd (typ 20 x 40 per m)	SW config'd (typ 20 x 40 per m)
Antenna Type	Air Core TEMR	Air Core TEMR	Air Core TEMR	Solid Core TEMR	Solid Core TEMR	Foam Core RETEM	Foam Core RETEM
Number of Array Elements	4	4	4	4	5/10/15 (5/m)	5/10/15 (5/m)	5/6/10/15 (5/m)
Array Element Spacing	Variable	9"	9"	9"	10"	10"	10"
Scan Width (nom)	Variable	36"	27"	27"	40"/80"/120"	40"/80"/120"	40"/40"/80"/120"
Array Height Above Ground (nom)	Variable	12" nom.	15"	15"	15"	15"	15"
Center Frequency (GHz)	~1.25 ?	~1.25 ?	~1.25 ?	1.05	1.05	1.25	1.25
Bandwidth ±3 dB flatness (MHz)	±130 ?	±130 ?	±130 ?	±350	±350	±850	±1100
Max Radiated Peak Power (mW)	0.148 ?	0.148 ?	0.148 ?	42 @ 27"	42 @ 27"	70 @ 30"	70 @ 30"
Impulse Amplitude (nom. V)	±20 ?	±20 ?	±20 ?	±40	±40	±20	±20
Impulse Rise Time (ps)	?	?	?	250	250	200	150
Impulse Peak Power (W)	16 ?	16 ?	16 ?	64	64	32	32
Typical Sampling Rate (kSamp/sec)	?	78	78	78	~500	~800	~1000
Sampler Bandwidth (MHz)	900	900	900	1000	3000	3000	3000
Software / Operating System	N/A	CMINE / DOS	CMINE / DOS	CMINE / DOS	NFAR / NT	NFAR / NT	NFAR / NT
Real-time Target Detection Algorithms	None	None	Sum Squared Average(SSA)	SSA, single blob detect	SSA, fuzzy clustering, multi blob detect	2nd deriv Filter, Fuzzy clustering, multi blob detect, add'l prototypes	2nd deriv Filter, Fuzzy clustering, multi blob detect, add'l prototypes

? Indicates direct measurement data not readily available.

In 1996, the Model 300 series EFPGR architecture was developed to support 3 meter wide vehicular deployment. The Model 301B EFGPR was demonstrated in the US Army's Vehicular Mounted Mine Detection System Advanced Technology Demonstration at temperate and arid sites during 1997. Results as tabulated by the Institute for Defense Analysis (IDA) are presented in a subsequent section of this report. Further test and research has led to the development of the Model 400 series. The Model 400 EFGPRs have incorporated significant engineering changes to support humanitarian demining operations in addition to stand-alone vehicular deployment. These changes improve detection performance for smaller (anti-personnel) land mines, provide a graphical user interface and man-portable deployment platform for humanitarian demining prototype, and support networked I/O, DGPS positioning and real time marking. An overview of the Model 400 series EFGPR is presented in the remainder of this section.

Model 400 Series EFGPR

GEO-CENTERS' Model 400 Series EFGPRs were initially developed for the US Army Humanitarian Demining Office at Fort Belvoir. The Model 400 series is designed to provide enhanced ability to detectsmall anti-personnel land mines, both metallic and non-metallic. The single array Model 401 system is designed to be fielded by a single person as required for humanitarian demining operations and is based on improvements demonstrated in a modified one meter Model 301 EFGPR (designated 301D in Table 1). The Model 401 man-portable demining system is deployed on a small motorized 3 wheel cart with a self-contained power supply (see Figure 5). This prototype one meter lane clearance system is currently being evaluated on mine test lanes and used as a development platform for advanced ATR algorithms. Initial blind and scored tests demonstrating real-time detection and marking show comparable results to the previous system which utilized post acquisition processing and GPS positioning of targets.

Figure 5. The Model 401 EFGPR on the 3 wheel man-portable platform developed for Fort Belvoir.

Model 400 series improvements over the base Model 301 systems include new Rolled Edge Transverse Electromagnetic (RETEM) antennas which provide substantial increases in both gain and upper bandwidth, along with improvements in RF components to take advantage of the enhanced radar bandwidth. Incorporating the same focusing methodology used in the Model 301, the Model 400 series has improved focus and resolution due to enhancements made in timing control and in the RF signal path. These improvements provide better detection capability and resolution of the smaller AP mine targets, while further improving signal to clutter for all landmine targets as compared to the Model 301B. Further improvements are being made to the automated target recognition algorithms to take advantage of the improved data quality. Model 400 series systems are smaller, lighter, and requires less power than their Model 301 counterparts. The Model 401 supports a single 1.5 meter, 6 antenna pair array to provide a one-meter detection swath. It is shown on the prototype man-portable platform developed for humanitarian demining in Figures 5 and 6.

Figure 6: Model 401 EFGPR mounted on a self-propelled power wagon.

The prototype humanitarian demining system provides real time marking capability through a series of spray nozzles located behind the detection array and in forward of the front wheels. In addition, a GPS receiver can be used to log real time position data to track both terrain covered and provide locations with target reports. The software for the Model 401 features an entirely new deminer-friendly graphical user interface (GUI) with a reduced set of options implemented via a touchscreen. Using the deminer GUI, the system can be operated through only the touch screen display. The operator advances down the track until an object is detected by the Model 401's ATR algorithms. The operator is then prompted by audible and visual alarms to stop, then to reverse direction. Upon reversing, the marker positions are tracked by a distance encoder. When the marking array crosses the detected object's ground location, the appropriate spray nozzle is triggered and the location is marked. Calibration is automatic and no longer requires a separate timing alignment module. A system diagnostic screen allows operation of built-in test functions.

The Model 403 EFGPR utilizes the same internal system components as the Model 401, but is designed to support vehicular deployment using arrays with 5 antenna pairs. The Model 403 system provides a standard rack mount package for the host electronics, and the forward mounted sensor arrays are connected to the host using 3 ten meter cables (one power and 2 signal). Figure 7 shows a photograph of the host electronics, a single array, and interconnect cables. Up to 3 arrays can be used, resulting in a nominal detection swath up to 3 meters wide. Average detection speeds of 6 kph can be maintained in a 3 meter wide configuration. Faster rates are possible by decreasing the scanned swath or using fewer arrays. The host software also provides support for networked functions such as real time data transfer, network time protocol (NTP) client, network input of position data, and other functions useful for integration to a multi-sensor system.

Under contract to the Commonwealth of Australia's Defence Science Technology Organisation (DSTO) in Salisbury, Australia, GEO-CENTERS' Technical Services Group recently completed delivery of a Model 403 EFGPR. The EFGPR is one of 3 primary detection sensors being integrated into the vehicular deployed Rapid Route and Area Mine Neutralisation System (RRAMNS) Capability Technology Demonstrator (CTD). The RRAMNS program is developing a route clearance capability for the Australian Department of Defense using GPR, metal detection, and forward looking camera systems. The CTD provides a single platform for the evaluation and fusion of multi-sensor land mine detection technologies. The 3 meter EFGPR array delivered to DSTO is shown deployed on a test platform in Figure 8. GEO-CENTERS is also providing engineering services for EFGPR integration, software development and test support under a Technical Assistance Agreement with DSTO.

3. EFGPR Evaluations

VMMD Advanced Technology Demonstration (ATD) Results

GEO-CENTERS VMMD system, incorporating a Model 301 3 meter EFGPR, passed an ATD in the summer of 1998. There were two test sites and each had on-road and off-road lanes. Each lane had buried (subsurface) and surface-laid metallic and non-metallic antitank mines. The Institute for Defense Analysis (IDA) report on the VMMD ATD (IDA document D-2203) breaks down the test results of GEO-CENTERS VMMD system the following ways:

SUMMARY OF ATD ON-ROAD PERFORMANCE:

Subsurface P_d	Subsurface P_d	Surface P_d	Surface P_d	FAR/m^2	FAR/m^2
99%	91%	100%	100%	0.056	0.032

SUMMARY OF ATD OFF-ROAD PERFORMANCE:

Subsurface P_d	Subsurface P_d	Surface P_d	Surface P_d	FAR/m^2	FAR/m^2
90%	70%	100%	100%	0.066	0.035

When averaged together, these results produce an average P_d of 93.75% and an average false alarm rate of .047/m^2. The IDA report also states that GEO-CENTERS "showed the best performance for on-road-subsurface mines"[1] and that GEO-CENTERS 301 EFGPR "performance exceeds the 90-percent confidence interval of all other contractors' GPRs"[2].

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[1] Draft IDA Report D-2203, pg. IV-3

[2] Draft IDA Report D-2203, pg. IV-6

Figure 7. GEO-CENTERS Model 401 EFGPR with single array, cables and host electronics.

Figure 8. Three meter wide Model 403 EFGPR arrays in initial testing at Australia's Defense Science and Technology Organisation (DSTO).

Analysis in Publications

A number of publications have utilized GEO-CENTERS Model 301B EFGPR data sets for analysis and algorithm development, or the time domain focusing approach as an element of their research in mine detection. A partial list of these references includes:

J.D. Schavemaker, E. den Breejan, F. Cremer, K. Schutte, K.W. Benoist, "Depth fustion for antipersonnel landmine detection", Proceedings, SPIE Conference on Detection and Remediation Technologies for Mines and Minelike Targets VI, Orlando, FL, Vol 4394, pp 1071-1081, April 2001.

Miroslaw Mystkowski and Paul D. Gader, "Adaptive Hidden Markov models for extended landmine detection", Proceedings, SPIE Conference on Detection and Remediation Technologies for Mines and Minelike Targets VI, Orlando, FL, Vol 4394, pp 476-482, April 2001.

Paul D. Gader, James M. Keller, Bruce N. Nelson, "Recognition Technology For the Detection of Buried Land Mines", IEEE Transactions on Fuzzy Systems, Special Issue on Recognition Technology, Vol. 9, No.1, pp.31-43, February 2001.

P. D. Gader, B. Nelson, H. Frigui, G. Vaillette, J. Keller, "Landmine Detection in Ground Penetrating Radar using Fuzzy Logic," Signal Processing, Special Issue on Fuzzy Logic in Signal Processing (Invited Paper), Vol. 80, No. 6, pp. 1069-1084, June 2000.

H.T. Haskett and J.T. Broach, "Mine detection performance by fusing ground penetrating radars and metal detector", Proceedings, SPIE Conference on Detection and Remediation Technologies for Mines and Minelike Targets V, Orlando, FL, pp 835-846, April 2000.

P.D. Gader, A.K. Hocaoglu, M. Mystkowski, and Y.Zhao, "Hidden Markov models and morphological neural networks for GPR-based landmine detection", Proceedings, SPIE Conference on Detection and Remediation Technologies for Mines and Minelike Targets V, Orlando, FL, pp 1096-1107, April 2000.

H. Raemer, C. Rappaport, E. Miller, and Roberta Young, "Validation Study of 3 Dimensional Ray-Based GPR Simulation Code", Proceedings, SPIE Conference on Detection and Remediation Technologies for Mines and Minelike Targets V, Orlando, FL, pp 1127-1139, April 2000.

P.D Gader, H.Frigui, B.N. Nelson, G. Vailette, and J.M. Keller, "New results in fuzzy set based detection of land mines with GPR", Proceedings, SPIE Conference on Detection and Remediation Technologies for Mines and Minelike Targets IV, Orlando, FL, pp 1075-1084, April 1999.

B.N. Nelson, P.D. Gader, J.M. Keller, "Fuzzy Set Information Fusion in Landmine Detection", Proceedings, SPIE Conference on Detection and Remediation Technologies for Mines and Minelike Targets IV, Orlando, FL, pp 1168-1178, April 1999.

H. Raemer, C. Rappaport, and E. Miller, "Frequency Domain Simulation of Focused Array Radar Returns from Buried Mines in Clutter", Proceedings, SPIE Conference on Detection and Remediation Technologies for Mines and Minelike Targets III, Orlando, FL, pp 754-764, April 1998.

A.Sahin, C.M. Rappaport, and A. M. Dean, Jr., "Design Considerations for Short-Time pulse TEMR Antennas Using Finite Difference Time Domain Algorithm", Proceedings, SPIE Conference on Detection and Remediation Technologies for Mines and Minelike Targets III, Orlando, FL, pp 784-793, April 1998.