



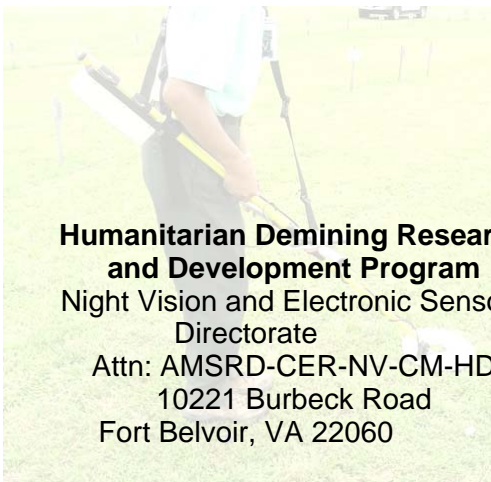
**Test Results of the Geophex GEM-3  
June 2004**



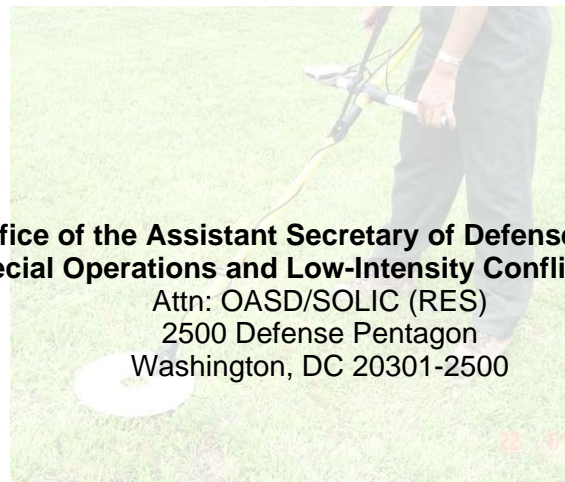
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# **Test Results of the Geophex GEM-3, June 2004**

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May 2005



## **PREFACE**

This document presents an analysis of the results of a blind test of the GEM-3 land-mine-detection system developed by Geophex, Ltd. The blind test took place at a temperate U.S. test site from June 14-25, 2004.

This document was prepared for the Director of Defense Research and Engineering, Office of the Under Secretary of Defense (Acquisition and Technology), under a task titled “Technical Support to Communication and Electronics Command Night Vision and Electronic Systems Directorate Mine Detection Program.”



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# EXECUTIVE SUMMARY

## INTRODUCTION

This document is an analysis of the results of a blind test of the GEM-3 Mine Detector and Discriminator landmine-detection system developed by Geophex, Ltd.. The GEM-3 was tested at a temperate U.S. test site in June 2004. The objective of the testing was to establish the current performance of the system.

## TESTING

A set of lanes 1.5 m wide by 25 m long was defined for testing. On-road lanes had a prepared gravel surface; off-road lanes were grassy. A variety of antitank (AT) and antipersonnel (AP) mines were buried at tactical depths. The mines were either metal (M) or low metal (LM). Emplaced clutter consisted of shell casings and shrapnel from bounding fragmentation mines. The shrapnel measured less than 1 cm on a side.

The GEM-3 was used to survey the lanes, and based on the data collected, we calculated detection probability ( $P_d$ ), which is the fraction of mines detected; false-alarm rate ( $FAR$ ), which is the number of false alarms per square meter; and rate of forward progress. False alarms are any alarms not matched to a target. The GEM-3 also computed a confidence value associated with each declaration. By using confidence values, we generated receiver-operator characteristic (ROC) curves.

During the test, Geophex operators distinguished between mine and clutter detections by placing chips of different colors on suspected locations of mines and clutter. Results in this report are divided into two categories: (1) mine declarations only, and (2) mine and clutter declarations. For each declaration, the GEM-3 also output an associated mine name in an attempt to perform target identification.

## SELECTED RESULTS

Tables ES-1 and ES-2 give  $P_d$ s and  $FAR$ s for on-road and off-road combined for mine declarations only and for mine and clutter declarations. Both tables also give the probability of false positive ( $P_{fp}$ ) data by type of clutter. Each Geophex operator covered a different group of on-road and off-road lanes, as shown in Table ES-3.

**Table ES-1. On and Off Road, Mine Declarations Only**

	$FAR (m^{-2})$		$P_d$				$P_{fp}$		
	Total	Background	AT-M	AP-M	AT-LM	AP-LM	Clutter 1	Clutter 2	Clutter 3
All Operators	0.27	0.18	1.00	1.00	0.42	0.90	0.01	0.53	0.42
Operator A	0.19	0.10	1.00	1.00	0.27	0.81	0.00	0.39	0.42
Operator B	0.45	0.31	1.00	1.00	0.43	1.00	0.03	0.76	0.44
Operator C	0.22	0.10	1.00	1.00	0.53	0.92	0.00	0.90	0.67

**Table ES-2. On and Off Road, Mine and Clutter Declarations**

	$FAR (m^{-2})$		$P_d$				$P_{fp}$		
	Total	Background	AT-M	AP-M	AT-LM	AP-LM	Clutter 1	Clutter 2	Clutter 3
All Operators	0.78	0.53	1.00	1.00	0.67	0.96	1.00	0.73	0.97
Operator A	0.67	0.37	1.00	1.00	0.53	0.88	1.00	0.58	0.95
Operator B	1.06	0.73	1.00	1.00	0.60	1.00	1.00	0.85	0.97
Operator C	0.62	0.39	1.00	1.00	0.87	1.00	1.00	0.95	0.95

**Table ES-3. Number of Lanes Surveyed for Each Operator**

Operator	Number of Missions		
	On Road	Off Road	Total
A	14	18	32
B	4	9	13
C	6	1	7
Total	24	28	52

## CONCLUSIONS

Overall, the GEM-3 was more sensitive to mines and characterized clutter with larger metal content, as well as to mines buried less deeply. Because of their low metal content and greater burial depths, mines in the AT-LM category had  $P_d$ s significantly lower than those for the other three mine categories. The road condition generally had little impact on the mine  $P_d$ s. The background  $FAR$  was significantly higher off road than on road, and the  $P_{fp}$ s for emplaced clutter were lower off road than on road.

Differences in operator performance were more pronounced in the off-road condition, where the  $FAR$  differed significantly. Operator C, with no prior GEM-3 experience, was able to match the performance of the more experienced operators in the on-road condition, while taking significantly more time to scan the lanes.

The effect of including clutter declarations, in addition to mine declarations, was to significantly increase the *FAR* with little or no gains in  $P_d$ . The exception was for the AT-LM category, where  $P_d$  increased by about 50%.

The GEM-3 did a good job discriminating among the mines it detected, and in many cases, it was able to identify mine models with few if any misidentifications.



## **I. INTRODUCTION**

### **A. THE HUMANITARIAN DEMINING PROGRAM**

The Humanitarian Demining Section of the U.S. Army Night Vision and Electronic Sensors Directorate (NVESD) is developing sensors to detect antitank (AT) and antipersonnel (AP) landmines. These sensors include the GEM-3 Mine Detector and Discriminator, built by Geophex Ltd. of Raleigh, N.C. The GEM-3 was tested at a temperate U.S. test site in June 2004. The objective of the testing was to establish the current performance of the system.

### **B. SYSTEM DESCRIPTION**

The Geophex GEM-3 is a hand-held, frequency-domain electromagnetic sensor operating in the band from about 270 Hz to 48 kHz. It consists of two transmit coils and a receive coil embedded in a circular plastic disk at the end of a telescopic wand having a maximum extension of about 2 m. Quadrature and in-phase electromagnetic spectra are recorded as the operator moves the sensor over the ground. Using a personal digital assistant (PDA) attached to the detector, these spectra are compared in real-time to a library of target spectra to determine the presence of a mine.

The GEM-3 is operated in essentially two modes, the detection mode and the discrimination mode. During the detection mode, the GEM-3 produces an audio signal in the presence of metallic objects. The operator attempts to localize the detected object by sweeping the GEM-3 over the ground and listening to the tonal changes of the audio signal. Once the potential mine has been localized, the operator switches to discrimination mode using the PDA attached to the detector. While the detector is moved slowly over the localized patch of ground, data are collected and compared to one or more libraries of mine signatures. After approximately 5 seconds, the PDA displays the results of the discrimination analysis, including the mine type, the mine library, and a confidence value.

### C. TEST PROCEDURES

A set of lanes, each 1.5 m wide by 25 m long, was defined for the purpose of the testing. Lanes with prepared gravel surfaces and unprepared grassy surfaces served to replicate on-road and off-road conditions. A variety of AT and AP mines were buried in the lanes at tactical depths. All mines were classified according to their metal content. Generally, a mine is considered to be metal (M) if the mine's case (or other major structural element) is metal. For example, the VS50, a plastic-cased AP mine, would be placed in the AP-M category because it contains a metal reinforcing plate. Mines that are largely nonmetal, except for some metal parts in the fuzing or firing mechanism, are considered low-metal (LM) mines. For example, the American antipersonnel M14 mine, whose metal content is less than 1 gram, would be placed in the AP-LM category. In addition to mine targets, characterized clutter was also buried in the test lanes. Clutter consisted of spent shell casings and shrapnel or "frag" from bounding fragmentation mines. Note that all mine and characterized clutter targets contained at least some metal.

Table I-1 shows the burial depths of the various mine categories and clutter.

**Table I-1. Burial Depths of Mine and Clutter Targets**

Category	Distance from Surface to Top of Target (in.)
AT-M	5
AP-M	0.5
AT-LM	3
AP-LM	1
Clutter	0.5

A complete survey of a lane by a detector system is referred to as a *mission*. The Geophex GEM-3 system completed four missions on a given lane, with two missions run in each direction.<sup>1</sup> The intention was to have each of two operators from Geophex complete two missions per lane, one run in each direction. In the end, three Geophex operators surveyed the lanes: Haoping Huang (A), Bill Sanfilipo (B), and Joe Seibert (C). Operator C had no prior experience using the GEM-3. Table I-2 shows the number of on road and off road lanes each operator surveyed.

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<sup>1</sup> Lanes were surveyed in both directions to minimize the use of visual cues during testing and also to make position-accuracy studies (discussed later) more meaningful.

**Table I-2. Number of Lanes Surveyed for Each Operator**

Operator	Number of Missions		
	On Road	Off Road	Total
A	14	18	32
B	4	9	13
C	6	1	7
Total	24	28	52

As the missions were in progress, Geophex operators marked the locations of suspected mines and suspected clutter with poker ships of different colors. These marks are referred to as *declarations*. For each declaration, data collectors recorded the declaration number, the confidence value, the mine type, and the mine library onto a data sheet. All but the declaration number are outputs of the detection algorithm as displayed on the PDA. Surveyors then measured the GPS coordinates of the declarations after the missions were completed. Generally speaking, Geophex operators designated mine declarations as those with confidence values between 6 and 10. Finally, the time to complete each mission was noted.

Based on the data collected, the detection probability, *FAR*, position accuracy, and rate of forward progress were computed. By using the confidence values, receiver-operator characteristic (ROC) curves were generated. Each of these measures is defined in detail in the next section; Chapter II gives the test results.

## **D. MEASURES OF EFFECTIVENESS**

### **1. Position Accuracy and Bias**

We begin our analysis by compiling the distribution of *miss distances* in the along-track and across-track directions. The miss distance is defined as the difference between the position of a target and a declaration. Miss-distance distributions generally derive their shape from two physical processes. First, a detector's response to clutter and noise contribute to a flat distribution—these declarations are distributed randomly in space with respect to a target because they are not associated with the detector's response to a target. Second, a detector's response to targets is peaked near target locations, generally displaying a Gaussian shape. The Gaussian describes the spatial response of the detector to the mines: the standard deviation of the Gaussian is related to the position accuracy of the detection process, and the mean of the Gaussian is related to the bias (or

offset) of the detection process.<sup>2</sup> This shape assumption (a Gaussian added to a flat distribution) is in fact an excellent match to the actual distributions.

To extract the position accuracy and bias of the detector, it is not adequate to compute the mean and standard deviation of the entire miss-distance distribution because random false alarms from clutter and noise contribute to these distributions. Ideally, we want to measure only the standard deviation and bias of the detector responding to a mine. We can separate these effects of detections and false alarms by fitting both the along-track and across-track distributions to the following function:

$$f(x) = c + a \cdot e^{-\frac{(x-m)^2}{2w^2}} \quad . \quad (\text{I-1})$$

The constant term  $c$  represents the flat (random) distribution; the Gaussian parameters  $a$ ,  $m$ , and  $w$  model the response of the detector system to the mines, with  $w$  and  $m$  representing the standard deviation and bias, respectively. The miss-distance data used in this analysis was binned in 5 cm bins, with the error in each bin taken to be the square root of the number of entries in the bin. If there were no entries in a bin, we took the error to be 1. The fits were performed by finding the function parameters of  $f$  which minimize the  $\chi^2$  of the fit, where  $\chi^2 = \sum_i (x_{\text{fit}} - x_i)^2 / \sigma_i^2$ , and  $i$  is the index of a given bin.

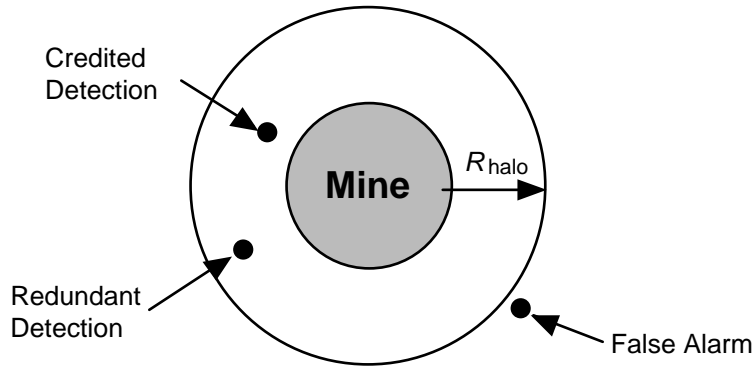
Chapter II, Section A, gives the position accuracy and bias results.

## 2. Detection Probability and False-Alarm Rate

Contractor declarations of potential target locations are either matched to an emplaced target, a “detection,” or not matched to a target, a “false alarm.” Declarations are matched to emplaced targets if the declaration is within a critical distance,  $R_{\text{halo}}$ , of the edge of the target. The value for  $R_{\text{halo}}$  is taken to be 15 cm. This distance criterion can result in more than one candidate declaration that matches a particular emplaced target. When there are redundant declarations within  $R_{\text{halo}}$ , the contractor is credited with a single detection of the target. Redundant detections are not counted as false alarms. If the declaration is within  $R_{\text{halo}}$  but outside the test lane, it is still scored as a valid detection. A declaration not within  $R_{\text{halo}}$  of any emplaced target and located within the test lane is considered a false alarm. These possible outcomes are illustrated in Figure I-1.

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<sup>2</sup> This discussion assumes that the Gaussian’s standard deviation and bias are due completely to the detector and ignores contributions such as survey errors. Since it is expected that the detector dominates these errors, this is probably a reasonable assumption.



**Figure I-1. A Pictorial Definition of Detections and False Alarms**

The detection probability ( $P_d$ ) and false-alarm rate ( $FAR$ ) are the two primary measures derived from this type of blind test. The detection probability is simply the fraction of the encountered mines that are detected:

$$P_d = \frac{\# \text{ mines detected}}{\# \text{ mines encountered}} . \quad (\text{I-2})$$

This probability is computed for each mine category, as well as for each mine model. The  $FAR$  is the measure of the number of false alarms per square meter of operation for the detector:

$$FAR = \frac{\# \text{ false alarms}}{\text{total lane area} - \text{area in halos}} . \quad (\text{I-3})$$

Ninety-percent confidence-level errors are computed on both the  $P_d$  and  $FAR$ . The 90-percent confidence-level errors on  $P_d$  are derived assuming a binomial distribution, using standard statistical procedures.<sup>3</sup> The lower error is the value for  $P_d$  that would yield the measured  $P_d$  (or greater) with a 5-percent probability; the upper error is the value for  $P_d$  that would yield the measured  $P_d$  (or less) with a 5-percent probability. The error in  $FAR$  is derived by assuming that the collection of false alarms is a counting exercise; hence the standard deviation in the number of false alarms is given by the square root of the number of false alarms. The 90-percent confidence-level errors are thus 1.65 times the standard deviation, a range that encompasses 90 percent of the statistical error in a normal distribution.

Chapter II, Section B, gives  $P_d$  and  $FAR$  results.

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<sup>3</sup> The computation for the confidence-level intervals on binomial distributions, performed by *MATLAB* in this analysis, is based on the discussion in N. L. Johnson, S. Kotz, and A. W. Kemp, *Univariate Discrete Distributions* (New York: John Wiley & Sons, 1993), pp. 124–130.

### 3. Characterized Clutter

In addition to natural, or background, clutter, the lanes contained characterized clutter (shells and shrapnel) that was emplaced as part of the design of the site. This characterized clutter requires additional analysis.

In general, the total *FAR* of a sensor is determined by properties of the natural environment as well as by the density of man-made clutter:

$$\text{total } FAR = \text{background } FAR + \rho_{cl}P_{fp}, \quad (\text{I-4})$$

where the background *FAR* is the false-alarm rate for that sensor against the natural environment of the site,  $\rho_{cl}$  is the man-made clutter density, and  $P_{fp}$  is the probability of false positive against man-made clutter (the probability that the emplaced clutter is called a mine).

We track the total *FAR*, the background *FAR*, and the  $P_{fp}$  for shells and fragments. Tracking the false positives against characterized clutter elucidates the discrimination capability of the sensor.

### 4. ROC Curves

For this test, Geophex operators provided a confidence value for each declaration, as output in real time from their detection algorithm. These confidence values<sup>4</sup> were based on how well the quadrature and in-phase electromagnetic spectra matched specified mine signatures in their model libraries. The higher the confidence value, the greater the certainty that a mine is present.

These alarm confidence values allow for the formation of ROC curves that relate  $P_d$  and *FAR*. These ROC curves can be more informative than the single-point performance measures computed in the absence of confidence values. The ROC curves give the cost in terms of the number of false alarms that it would take to detect a given percentage of mines. These curves can shed light on the ease or difficulty with which mines of a specific type are detected. ROC curves appear in Appendix D.

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<sup>4</sup> Note that this confidence value, which is an indication of the operator's confidence in a declaration, should not be confused with the confidence-level errors discussed in Section I.D.2, which are measures of statistical accuracy.

## **5. Rate of Advance**

We measure the rate of advance of the operators by computing the number of seconds per square meter spent surveying the lanes. Chapter II, Section C, gives the results for all operators combined.

## **6. Target Identification**

Geophex used a target-ID algorithm to compare the signals of the GEM-3 to a library of mine signatures. The degree to which the present signal matched each of the mine signatures stored in the library was quantified. The best match was determined, and the output, consisting of a mine name, mine library, and confidence value, was displayed automatically on the PDA. We compared the ground truth with the mine names associated with each declaration. Results appear in Appendix D.

## **7. Meteorological Data**

Appendix E gives air temperature, soil moisture, and precipitation data at the test site for the period 15–24 June 2004.



## II. TEST RESULTS

### A. POSITION ACCURACY AND BIAS

As discussed in Chapter I, miss-distance distributions were constructed against both AP and AT targets and fit to Eq. I-1. We grouped on-road and off-road data and data against metal and low-metal targets because there were no substantive differences in the distributions for these groups and the combined data provided better statistical samples for the fits. Table II-1 gives the results for the fits for AP and AT mines. The detailed distributions, as well as the overall fits, can be seen in Appendix A. For both AT and AP mines, comparing the 3-standard-deviation widths with the sum of mine and halo radii ( $R_{\text{mine}} + R_{\text{halo}}$ ) shows that the 15 cm  $R_{\text{halo}}$  is adequate for capturing all detections. Even for AP mines, whose radii are approximately 4 cm, the 3-standard deviation width is approximately 15 cm, which is less than the sum of mine and halo radii (~19 cm).

**Table II-1. Along-Track and Across-Track Biases and Standard Deviations Against AP and AT Mines for On and Off Road Combined**

	Bias		Width (Standard Deviation)	
	Along Track (m)	Across Track (m)	Along Track (m)	Across Track (m)
AP	0.01	0.00	0.03	0.03
AT	0.01	0.00	0.04	0.05

### B. FAR AND $P_d$ SUMMARIES

In this section we summarize the  $P_d$  vs.  $FAR$  results. We pay particular attention to how the performance depends on road conditions, metal content of targets, depth of targets, and size of targets.

Tables II-2 through II-4 give the  $FAR$ ,  $P_d$ , and  $P_{fp}$  summaries for Geophex. For each table, results are listed for (1) mine declarations only and (2) mine and clutter declarations. Results for the combined on-road and off-road conditions are given in Table II-2. The on-road and off-road results are given in Tables II-3 and II-4, respectively. The Geophex sensor exhibited the following properties:

- By far the most difficult mine target for the Geophex sensor was the AT-LM category. These mines are buried more deeply than those in the AP-LM category.
- The background *FAR* was significantly higher off road than on road.
- The road condition had little impact on the mine  $P_d$ s, except for AP-LM, which was lower off road than on road for mine declarations only, and for AT-LM, which was lower off road than on road for mine and clutter declarations.
- Shells were almost always correctly characterized as clutter.
- For AP-LM mines, on and off road combined, the  $P_d$  increased by 7% as the *FAR* increased by a factor of 3 when going from mine declarations only to mine and clutter declarations.
- For AT-LM mines, on and off road combined, the  $P_d$  increased by 60% as the *FAR* increased by a factor of 3 when going from mine declarations only to mine and clutter declarations.
- For mine declarations only, the road condition had no impact on the  $P_{fp}$  for Clutter 1, but for Clutter 2 and 3  $P_{fps}$  were significantly higher on road than off road.

**Table II-2. Geophex FAR and  $P_d$  by Mine Category for On and Off Road Combined, for Mine Declarations Only, and for Mine and Clutter Declarations (90% Confidence-Level Limits)**

		<b>FAR (m<sup>-2</sup>)</b>	
		avg.	90% CL range
<b>All Operators</b>	<b>Mine</b>	total	0.27   0.29 - 0.25
	<b>Declarations</b>	bkgnd	0.18   0.20 - 0.17
		<b><math>P_d</math></b>	
		avg.	90% CL range
<b>On and Off</b>	<b>Road</b>	AT-M	1.00   1.00 - 0.93
		AP-M	1.00   1.00 - 0.95
		AT-LM	0.42   0.51 - 0.34
		AP-LM	0.90   0.94 - 0.84

		<b><math>P_{fp}</math></b>	
		avg.	90% CL range
Clutter 1		0.01	0.03 - 0.00
Clutter 2		0.53	0.60 - 0.47
Clutter 3		0.42	0.49 - 0.36

		<b>FAR (m<sup>-2</sup>)</b>	
		avg.	90% CL range
<b>All Operators</b>	<b>Mine and Clutter</b>	total	0.78   0.82 - 0.75
	<b>Declarations</b>	bkgnd	0.53   0.56 - 0.50

		<b><math>P_d</math></b>	
		avg.	90% CL range
<b>On and Off</b>	<b>Road</b>	AT-M	1.00   1.00 - 0.93
		AP-M	1.00   1.00 - 0.95
		AT-LM	0.67   0.75 - 0.58
		AP-LM	0.96   0.98 - 0.91

		<b><math>P_{fp}</math></b>	
		avg.	90% CL range
Clutter 1		1.00	1.00 - 0.98
Clutter 2		0.73	0.78 - 0.67
Clutter 3		0.97	0.99 - 0.94



**Table II-4. Geophex FAR and  $P_d$  by Mine Category for Off Road, for Mine Declarations Only, and for Mine and Clutter Declarations (90% Confidence-Level Limits)**

		<b>FAR (m<sup>-2</sup>)</b>	
		avg.	90% CL range
<b>All Operators</b>	total	0.36	0.39 - 0.33
	bkgnd	0.31	0.34 - 0.28

*Mine Declarations Only*

		<b><math>P_d</math></b>	
		avg.	90% CL range
<i>Off Road</i>	AT-M	1.00	1.00 - 0.86
	AP-M	1.00	1.00 - 0.91
	AT-LM	0.39	0.52 - 0.26
	AP-LM	0.85	0.92 - 0.74

		<b><math>P_{fp}</math></b>	
		avg.	90% CL range
Clutter 1	0.00	0.03 - 0.00	
Clutter 2	0.34	0.43 - 0.26	
Clutter 3	0.22	0.30 - 0.15	

		<b>FAR (m<sup>-2</sup>)</b>	
		avg.	90% CL range
<b>All Operators</b>	total	1.07	1.12 - 1.01
	bkgnd	0.84	0.88 - 0.79

*Mine and Clutter Declarations*

		<b><math>P_d</math></b>	
		avg.	90% CL range
<i>Off Road</i>	AT-M	1.00	1.00 - 0.86
	AP-M	1.00	1.00 - 0.91
	AT-LM	0.59	0.72 - 0.46
	AP-LM	0.94	0.98 - 0.86

		<b><math>P_{fp}</math></b>	
		avg.	90% CL range
Clutter 1	1.00	1.00 - 0.97	
Clutter 2	0.67	0.75 - 0.58	
Clutter 3	0.99	1.00 - 0.95	

#### **D. RATE OF ADVANCE**

We measured the rate of advance of the operators by computing the number of seconds per square meter spent surveying the lanes. Table II-5 gives the results. We computed the rate of advance for each of the Geophex operators for on road and off road separately. Recall that Operator C had no prior experience using the GEM-3. Also, operators did not cover the same sets of lanes, and background FARs could vary from lane to lane.

**Table II-5. Average Rate of Advance by Operator and Road Condition**

Operator	Avg. Advance Rate (sec/m <sup>2</sup> )	
	On Road	Off Road
A	75	114
B	78	191
C	186	315

### III. CONCLUSIONS

Overall, the GEM-3 was more sensitive to mines and characterized clutter with larger metal content, as well as to mines buried less deeply. Because of their low metal content and greater burial depths, mines in the AT-LM category had  $P_d$ s significantly lower than those for the other three mine categories. The road condition generally had little impact on the mine  $P_d$ s. The background  $FAR$  was significantly higher off road than on road, and the  $P_{fp}$ s for emplaced clutter were lower off road than on road.

Differences in operator performance were more pronounced in the off-road condition, where the  $FAR$  differed significantly. Operator C, with no prior GEM-3 experience, was able to match the performance of the more experienced operators in the on-road condition, while taking significantly more time to scan the lanes.

The effect of including clutter declarations, in addition to mine declarations, was to significantly increase the  $FAR$  with little or no gains in  $P_d$ . The exception was for the AT-LM category, where  $P_d$ s increased by about 50%.

The GEM-3 did a good job discriminating specific mines that it detected, and in many cases, was able to identify mine models with few if any misidentifications.



## GLOSSARY

$\rho_{cl}$	man-made clutter density
AP	antipersonnel
AT	antitank
ATR	automated target recognition
CV	confidence value
EDIT	Electromagnetic-Wave Detection and Imaging Transceiver
EFGPR	Energy-Focused Ground-Penetrating Radar
EM	electromagnetic wave
FAR	false-alarm rate
GPS	Global Positioning System
LM	low metal
M	metal
NVESD	Night Vision and Electronic Sensors Directorate
$P_d$	detection probability
$P_{fp}$	probability of false positive
ROC	receiver-operator characteristic
S/N	signal to noise



## APPENDIX A—POSITION RESOLUTION PLOTS

The data points in Figure A-1 are the measured along-track and across-track miss distance distributions for AP and AT mines as obtained by Geophex. When Eq. I-1 is fit to these distributions (the solid curves in the figures), biases (means) and resolutions (standard deviations) can be extracted. These are listed in each figure. Because no substantive differences appear in any of the on-road/off-road or metal/low-metal distributions, these cases are grouped in the plots. The y-axis values correspond to the number of declarations.

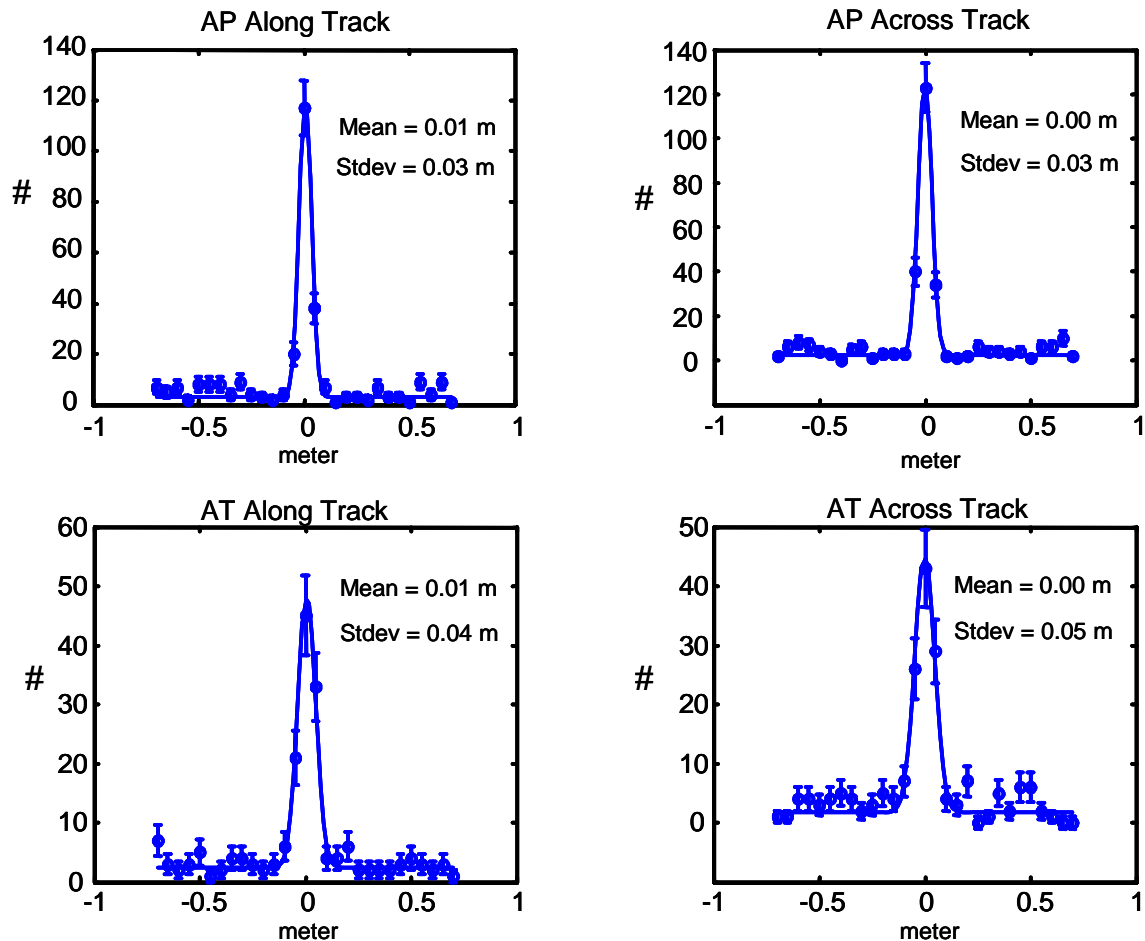


Figure A-1. Along-Track and Across-Track Miss Distance Distributions for AP Mines (top) and AT Mines (bottom) for the Geophex System



## APPENDIX B—DETECTION BY OPERATOR

**Table B-1. Operator A—Geophex FAR and  $P_d$  by Mine Category for On and Off Road Combined, for Mine Declarations Only and for Mine and Clutter Declarations (90% Confidence-Level Limits)**

<b>Operator A</b>	<b>FAR (m<sup>-2</sup>)</b>					
		avg.	90% CL range			
	total	0.19	0.23 - 0.16			
<i>Mine</i>	bkgnd	0.10	0.12 - 0.07			
<i>Declarations Only</i>						
<i>On and Off Road</i>	<b><math>P_d</math></b>			<b><math>P_{fp}</math></b>		
		avg.	90% CL range	avg.	90% CL range	
	AT-M	1.00	1.00 - 0.81	Clutter 1	0.00	0.05 - 0.00
	AP-M	1.00	1.00 - 0.83	Clutter 2	0.39	0.50 - 0.28
	AT-LM	0.27	0.43 - 0.14	Clutter 3	0.42	0.53 - 0.31
AP-LM	0.81	0.90 - 0.68				
<i>Operator A</i>						
<b>FAR (m<sup>-2</sup>)</b>						
	avg.	90% CL range				
total	0.67	0.73 - 0.61				
bkgnd	0.37	0.42 - 0.33				
<i>Mine and Clutter Declarations</i>						
<i>On and Off Road</i>	<b><math>P_d</math></b>			<b><math>P_{fp}</math></b>		
		avg.	90% CL range	avg.	90% CL range	
	AT-M	1.00	1.00 - 0.81	Clutter 1	1.00	1.00 - 0.95
	AP-M	1.00	1.00 - 0.83	Clutter 2	0.58	0.69 - 0.47
	AT-LM	0.53	0.69 - 0.37	Clutter 3	0.95	0.99 - 0.88
AP-LM	0.88	0.95 - 0.77				

**Table B-2. Operator A—Geophex FAR and  $P_d$  by Mine Category for On Road, for Mine Declarations Only and for Mine and Clutter Declarations (90% Confidence-Level Limits)**

		<b>FAR (m<sup>-2</sup>)</b>				<b>P<sub>fp</sub></b>	
		avg.	90% CL range	avg.	90% CL range	avg.	90% CL range
<b>Operator A</b>	<i>Mine</i>	total	0.14	0.17 - 0.11			
		bkgnd	0.02	0.03 - 0.01			
<i>Declarations Only</i>							
<i>On Road</i>		<b>P<sub>d</sub></b>					
		avg.	90% CL range	avg.	90% CL range	avg.	90% CL range
		AT-M	1.00	1.00 - 0.76	Clutter 1	0.00	0.06 - 0.00
		AP-M	1.00	1.00 - 0.85	Clutter 2	0.60	0.72 - 0.47
		AT-LM	0.48	0.64 - 0.33	Clutter 3	0.66	0.77 - 0.53
		AP-LM	0.91	0.97 - 0.78			
<i>Mine and Clutter Declarations</i>							
<i>On Road</i>		<b>FAR (m<sup>-2</sup>)</b>					
		avg.	90% CL range	avg.	90% CL range	avg.	90% CL range
		total	0.37	0.41 - 0.32			
		bkgnd	0.11	0.14 - 0.09			
<i>On Road</i>		<b>P<sub>d</sub></b>					
		avg.	90% CL range	avg.	90% CL range	avg.	90% CL range
		AT-M	1.00	1.00 - 0.76	Clutter 1	1.00	1.00 - 0.94
		AP-M	1.00	1.00 - 0.85	Clutter 2	0.70	0.81 - 0.58
		AT-LM	0.79	0.90 - 0.64	Clutter 3	0.94	0.98 - 0.85
		AP-LM	0.94	0.99 - 0.82			

**Table B-3. Operator A— Geophex FAR and  $P_d$  by Mine Category for Off Road, for Mine Declarations Only and for Mine and Clutter Declarations (90% Confidence-Level Limits)**

		<b>FAR (m<sup>-2</sup>)</b>		
		avg.	90% CL range	
<b>Operator A</b>	<b>Mine</b>	total	0.22	0.25 - 0.19
	<b>Declarations Only</b>	bkgnd	0.19	0.21 - 0.16

		<b><math>P_d</math></b>	
		avg.	90% CL range
<b>Off Road</b>	AT-M	1.00	1.00 - 0.78
	AP-M	1.00	1.00 - 0.87
	AT-LM	0.30	0.47 - 0.16
	AP-LM	0.77	0.89 - 0.61

		<b><math>P_{fp}</math></b>	
		avg.	90% CL range
Clutter 1	0.00	0.05 - 0.00	
Clutter 2	0.19	0.30 - 0.11	
Clutter 3	0.19	0.30 - 0.11	

		<b>FAR (m<sup>-2</sup>)</b>		
		avg.	90% CL range	
<b>Operator A</b>	<b>Mine and Clutter</b>	total	0.83	0.89 - 0.77
	<b>Declarations</b>	bkgnd	0.62	0.68 - 0.57

		<b><math>P_d</math></b>	
		avg.	90% CL range
<b>Off Road</b>	AT-M	1.00	1.00 - 0.78
	AP-M	1.00	1.00 - 0.87
	AT-LM	0.52	0.69 - 0.35
	AP-LM	0.90	0.97 - 0.76

		<b><math>P_{fp}</math></b>	
		avg.	90% CL range
Clutter 1	1.00	1.00 - 0.95	
Clutter 2	0.54	0.66 - 0.43	
Clutter 3	1.00	1.00 - 0.95	

**Table B-4. Operator B—Geophex FAR and  $P_d$  by Mine Category for On and Off Road Combined, for Mine Declarations Only and for Mine and Clutter Declarations (90% Confidence-Level Limits)**

		<b>FAR (m<sup>-2</sup>)</b>	
		avg.	90% CL range
<b>Operator B</b>	<b>Mine</b>		
	<b>Declarations Only</b>		
	total	0.45	0.50 - 0.40
	bkgnd	0.31	0.35 - 0.27

		<b><math>P_d</math></b>	
		avg.	90% CL range
<b>On and Off Road</b>	AT-M	1.00	1.00 - 0.81
	AP-M	1.00	1.00 - 0.83
	AT-LM	0.43	0.60 - 0.28
	AP-LM	1.00	1.00 - 0.93

		<b><math>P_{fp}</math></b>	
		avg.	90% CL range
	Clutter 1	0.03	0.10 - 0.01
	Clutter 2	0.76	0.84 - 0.65
	Clutter 3	0.44	0.55 - 0.33

		<b>FAR (m<sup>-2</sup>)</b>	
		avg.	90% CL range
<b>Operator B</b>	<b>Mine and Clutter</b>		
	<b>Declarations</b>		
	total	1.06	1.14 - 0.98
	bkgnd	0.73	0.80 - 0.67

		<b><math>P_d</math></b>	
		avg.	90% CL range
<b>On and Off Road</b>	AT-M	1.00	1.00 - 0.81
	AP-M	1.00	1.00 - 0.83
	AT-LM	0.60	0.75 - 0.43
	AP-LM	1.00	1.00 - 0.93

		<b><math>P_{fp}</math></b>	
		avg.	90% CL range
	Clutter 1	1.00	1.00 - 0.95
	Clutter 2	0.85	0.92 - 0.76
	Clutter 3	0.97	0.99 - 0.90

**Table B-5. Operator B—Geophex FAR and  $P_d$  by Mine Category for On Road, for Mine Declarations Only and for Mine and Clutter Declarations (90% Confidence-Level Limits)**

		<b>FAR (m<sup>-2</sup>)</b>				<b>P<sub>fp</sub></b>	
		avg.	90% CL range	avg.	90% CL range	avg.	90% CL range
<b>Operator B</b>	<i>Mine</i>	total	0.24	0.31 - 0.18			
		bkgnd	0.03	0.05 - 0.01			
<i>Declarations Only</i>							
<i>On Road</i>		<b>P<sub>d</sub></b>					
		avg.	90% CL range	avg.	90% CL range	avg.	90% CL range
		AT-M	1.00	1.00 - 0.47	Clutter 1	0.11	0.30 - 0.02
		AP-M	1.00	1.00 - 0.47	Clutter 2	0.89	0.98 - 0.70
		AT-LM	0.22	0.55 - 0.04	Clutter 3	0.58	0.77 - 0.37
		AP-LM	1.00	1.00 - 0.83			
<i>Mine and Clutter Declarations</i>							
<i>On Road</i>		<b>FAR (m<sup>-2</sup>)</b>					
		avg.	90% CL range	avg.	90% CL range	avg.	90% CL range
		total	0.59	0.70 - 0.48			
		bkgnd	0.22	0.28 - 0.15			
		<b>P<sub>d</sub></b>					
		avg.	90% CL range	avg.	90% CL range	avg.	90% CL range
		AT-M	1.00	1.00 - 0.47	Clutter 1	1.00	1.00 - 0.85
		AP-M	1.00	1.00 - 0.47	Clutter 2	0.89	0.98 - 0.70
		AT-LM	0.33	0.66 - 0.10	Clutter 3	0.89	0.98 - 0.70
		AP-LM	1.00	1.00 - 0.83			

**Table B-6. Operator B— Geophex FAR and  $P_d$  by Mine Category for Off Road, for Mine Declarations Only and for Mine and Clutter Declarations (90% Confidence-Level Limits)**

		<b>FAR (m<sup>-2</sup>)</b>		
		avg.	90% CL range	
<b>Operator B</b>	<b>Mine</b>	total	0.65	0.72 - 0.57
	<b>Declarations Only</b>	bkgnd	0.57	0.64 - 0.50

		<b><math>P_d</math></b>	
		avg.	90% CL range
<b>Off Road</b>	AT-M	1.00	1.00 - 0.65
	AP-M	1.00	1.00 - 0.72
	AT-LM	0.50	0.72 - 0.28
	AP-LM	1.00	1.00 - 0.87

		<b><math>P_{fp}</math></b>	
		avg.	90% CL range
Clutter 1	0.00	0.08 - 0.00	
Clutter 2	0.57	0.71 - 0.42	
Clutter 3	0.24	0.39 - 0.13	

		<b>FAR (m<sup>-2</sup>)</b>		
		avg.	90% CL range	
<b>Operator B</b>	<b>Mine and Clutter</b>	total	1.53	1.64 - 1.42
	<b>Declarations</b>	bkgnd	1.25	1.35 - 1.14

		<b><math>P_d</math></b>	
		avg.	90% CL range
<b>Off Road</b>	AT-M	1.00	1.00 - 0.65
	AP-M	1.00	1.00 - 0.72
	AT-LM	0.69	0.87 - 0.45
	AP-LM	1.00	1.00 - 0.87

		<b><math>P_{fp}</math></b>	
		avg.	90% CL range
Clutter 1	1.00	1.00 - 0.92	
Clutter 2	0.84	0.93 - 0.70	
Clutter 3	1.00	1.00 - 0.92	

**Table B-7. Operator C—Geophex FAR and  $P_d$  by Mine Category for On and Off Road Combined, for Mine Declarations Only and for Mine and Clutter Declarations (90% Confidence-Level Limits)**

		<b>FAR (m<sup>-2</sup>)</b>	
		avg.	90% CL range
<b>Operator C</b>	<b>Mine</b>		
	<b>Declarations Only</b>		
	total	0.22	0.27 - 0.18
	bkgnd	0.10	0.13 - 0.06

		<b><math>P_d</math></b>	
		avg.	90% CL range
<b>On and Off Road</b>	AT-M	1.00	1.00 - 0.61
	AP-M	1.00	1.00 - 0.76
	AT-LM	0.53	0.76 - 0.30
	AP-LM	0.92	1.00 - 0.66

		<b><math>P_{fp}</math></b>	
		avg.	90% CL range
	Clutter 1	0.00	0.13 - 0.00
	Clutter 2	0.90	0.98 - 0.73
	Clutter 3	0.67	0.83 - 0.46

		<b>FAR (m<sup>-2</sup>)</b>	
		avg.	90% CL range
<b>Operator C</b>	<b>Mine and Clutter</b>		
	<b>Declarations</b>		
	total	0.62	0.70 - 0.54
	bkgnd	0.39	0.46 - 0.32

		<b><math>P_d</math></b>	
		avg.	90% CL range
<b>On and Off Road</b>	AT-M	1.00	1.00 - 0.61
	AP-M	1.00	1.00 - 0.76
	AT-LM	0.87	0.98 - 0.64
	AP-LM	1.00	1.00 - 0.78

		<b><math>P_{fp}</math></b>	
		avg.	90% CL range
	Clutter 1	1.00	1.00 - 0.87
	Clutter 2	0.95	1.00 - 0.79
	Clutter 3	0.95	1.00 - 0.79

**Table B-8. Operator C—Geophex FAR and  $P_d$  by Mine Category for On Road, for Mine Declarations Only and for Mine and Clutter Declarations (90% Confidence-Level Limits)**

		<b>FAR (m<sup>-2</sup>)</b>					
		avg.	90% CL range				
<b>Operator C</b>	<i>Mine</i>	total	0.21	0.26 - 0.16			
		bkgnd	0.07	0.09 - 0.04			
<i>Declarations Only</i>							
<i>On Road</i>		<b><math>P_d</math></b>		<b><math>P_{fp}</math></b>			
		avg.	90% CL range	avg.	90% CL range		
		AT-M	1.00	1.00 - 0.55	Clutter 1	0.00	0.15 - 0.00
		AP-M	1.00	1.00 - 0.72	Clutter 2	0.95	1.00 - 0.77
		AT-LM	0.50	0.74 - 0.26	Clutter 3	0.68	0.85 - 0.47
		AP-LM	1.00	1.00 - 0.76			
<b>Operator C</b>		<b>FAR (m<sup>-2</sup>)</b>					
		avg.	90% CL range				
<i>Mine and Clutter</i>		total	0.54	0.62 - 0.46			
<i>Declarations</i>		bkgnd	0.29	0.35 - 0.23			
<i>On Road</i>		<b><math>P_d</math></b>		<b><math>P_{fp}</math></b>			
		avg.	90% CL range	avg.	90% CL range		
		AT-M	1.00	1.00 - 0.55	Clutter 1	1.00	1.00 - 0.85
		AP-M	1.00	1.00 - 0.72	Clutter 2	0.95	1.00 - 0.77
		AT-LM	0.86	0.97 - 0.61	Clutter 3	1.00	1.00 - 0.85
		AP-LM	1.00	1.00 - 0.76			

**Table B-9. Operator C— Geophex FAR and  $P_d$  by Mine Category for Off Road, for Mine Declarations Only and for Mine and Clutter Declarations (90% Confidence-Level Limits)**

		<b>FAR (m<sup>-2</sup>)</b>		
		avg.	90% CL range	
<b>Operator C</b>	<b>Mine</b>	total	0.33	0.49 - 0.17
	<b>Declarations Only</b>	bkgnd	0.28	0.42 - 0.13

		<b><math>P_d</math></b>	
		avg.	90% CL range
<b>Off Road</b>	AT-M	1.00	1.00 - 0.05
	AP-M	1.00	1.00 - 0.22
	AT-LM	1.00	1.00 - 0.05
	AP-LM	0.00	0.95 - 0.00

		<b><math>P_{fp}</math></b>	
		avg.	90% CL range
Clutter 1	0.00	0.77 - 0.00	
Clutter 2	0.50	0.97 - 0.03	
Clutter 3	0.50	0.97 - 0.03	

		<b>FAR (m<sup>-2</sup>)</b>		
		avg.	90% CL range	
<b>Operator C</b>	<b>Mine and Clutter</b>	total	1.12	1.41 - 0.83
	<b>Declarations</b>	bkgnd	1.00	1.28 - 0.73

		<b><math>P_d</math></b>	
		avg.	90% CL range
<b>Off Road</b>	AT-M	1.00	1.00 - 0.05
	AP-M	1.00	1.00 - 0.22
	AT-LM	1.00	1.00 - 0.05
	AP-LM	1.00	1.00 - 0.05

		<b><math>P_{fp}</math></b>	
		avg.	90% CL range
Clutter 1	1.00	1.00 - 0.22	
Clutter 2	1.00	1.00 - 0.22	
Clutter 3	0.50	0.97 - 0.03	



## APPENDIX C—ROC CURVES

In this appendix, we show the receiver-operator characteristic (ROC) curves for the Geophex GEM-3. ROC curves are given for the four mine categories—AT–M, AT–LM, AP–M, and AP–LM (see Chapter II). Results are for on and off road combined. The far right points from each of the curves correspond to the  $P_d$ s and  $FAR$ s in the tables from Chapter II. Figure D-1 is for all the surveyed lanes. Figure D-2 compares operators A, B, and C for surveys of the on-road lanes for AT–LM and AP–LM mines using only the mine declarations. Figure D-3 compares operators A and B for surveys of the off-road lanes for AT–LM and AP–LM mines using only the mine declarations (operator C only surveyed one off-road lane). In Figures D-2 and D-3, note that the  $FAR$ s are different for each operator. For the off-road lanes, the  $FAR$  for Operator B is three times greater than for Operator A, but Operator A fails to achieve a  $P_d$  of 1. The performance of Operator C, who had no prior experience using the GEM-3, is about as good as or better than the other operators for the on-road lanes.

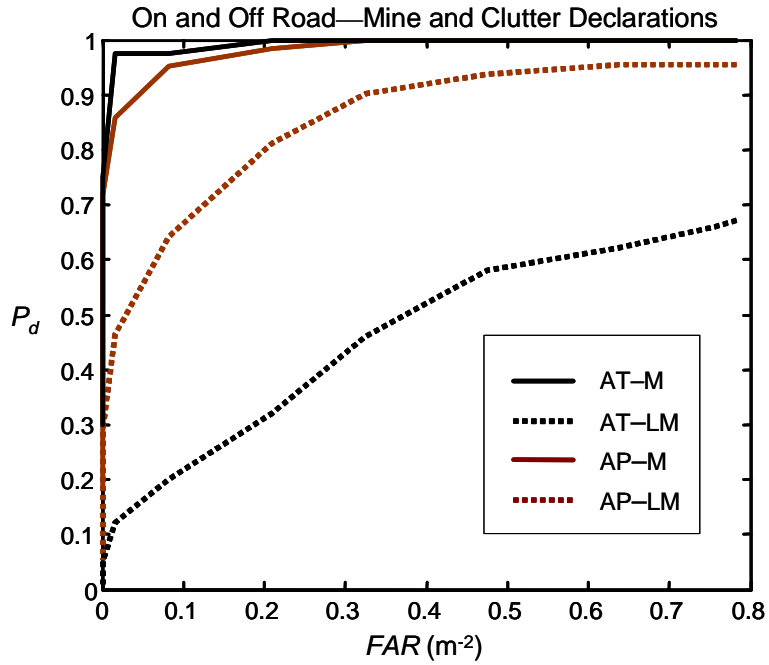


Figure C-1. ROC Curves for Mine and Clutter Declarations, On and Off Road Combined

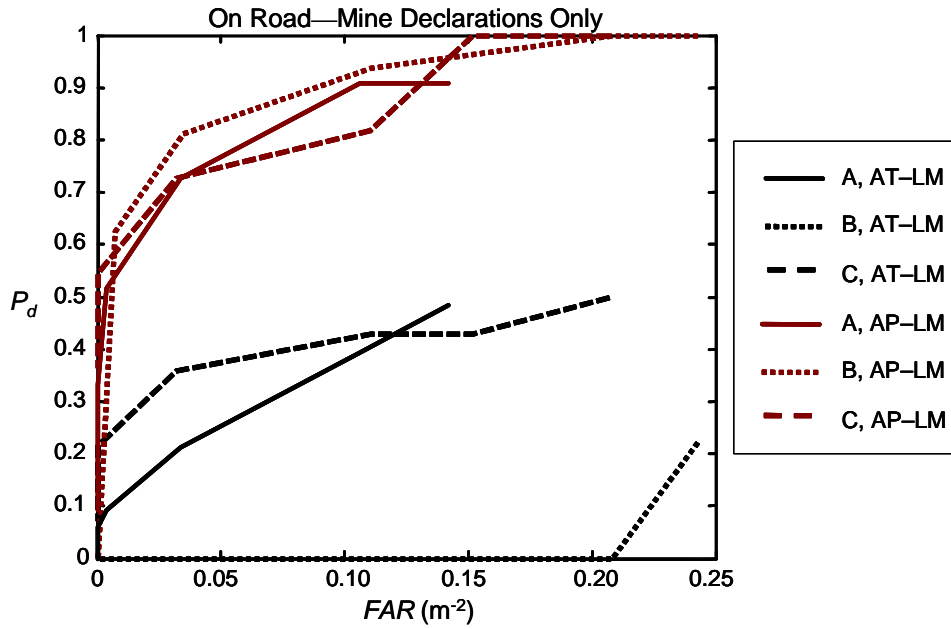


Figure C-2. ROC Curves for On-Road Lanes by Operators A, B, and C for AT-LM and AP-LM Mines for Mine Declarations Only

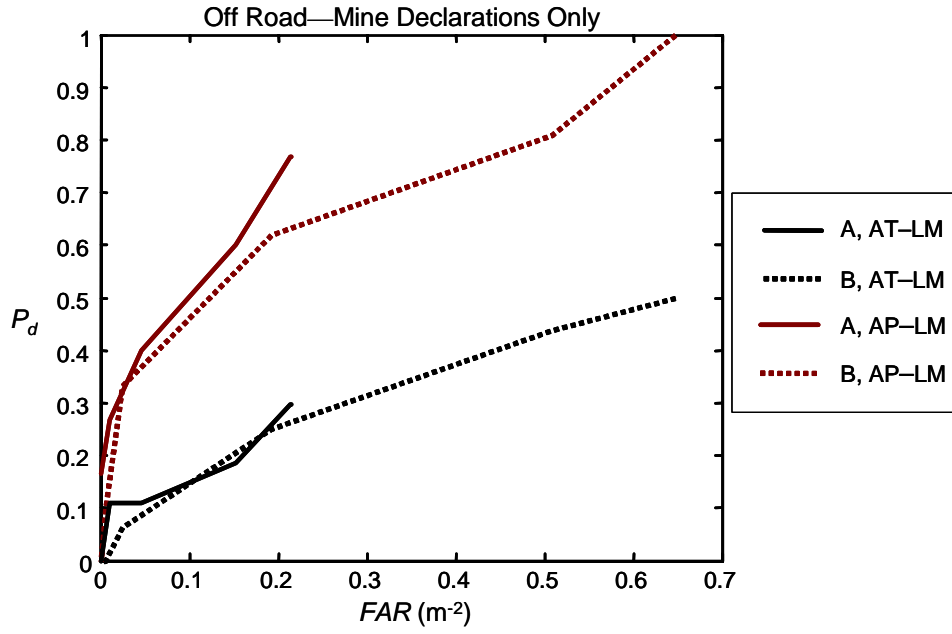


Figure C-3. ROC Curves for Off-Road Lanes by Operators A and B for AT-LM and AP-LM Mines for Mine Declarations Only



## **APPENDIX D—GEOPHEX TARGET IDENTIFICATION RESULTS**

Geophex used a target-ID algorithm to compare the signals of the GEM-3 with a library of mine signatures. The degree to which the present signal matched each of the mine signatures stored in the library was quantified. The closest matched mine was identified, and a confidence value was computed.

Table D-1 shows the accuracy of their mine identifications for mine declarations only. The left-most column lists the mine and clutter types buried on the lanes that Geophex scanned. The top row of the table lists the various mine types that were declared by Geophex. The table includes data from detections only. Table D-2 shows the results for mine and clutter declarations.

The following general conclusions are made with reference to Tables D-1 and D-2:

- 89% of the detected mines were correctly identified as mines. Of those correctly identified as mines, 74% were correctly identified by specific mine model.
- When detected, 5 mine models (6, 7, 8, 9, and 14) were identified correctly 100 percent of the time.
- Three mine models (5, 10, and 12) were almost always misidentified.

**Table D-1. Results of Geophex Mine Declaration Only Target Identifications**

Truth	Type	Mine Declarations Only															Total
		Mine 1	Mine 2	Mine 3	Mine 4	Mine 5	Mine 6	Mine 7	Mine 8	Mine 9	Mine 10	Mine 11	Mine 12	Mine 13	Mine 14	SIM	
Mine 1	AP-LM	37		1	1								1		3	43	
Mine 2	AT-M		19	4								1				24	
Mine 3	AP-M	1		15												16	
Mine 4	AT-LM				1								3			4	
Mine 5	AP-LM	3				1									9	13	
Mine 6	AP-M						16									16	
Mine 7	AT-M							16								16	
Mine 8	AT-LM								16							16	
Mine 9	AP-LM									32						32	
Mine 10	AP-LM	8			2	2									1	13	
Mine 11	AP-M		1	2								13				16	
Mine 12	AT-LM				3								3			6	
Mine 13	AT-LM	1			3								8		4	16	
Mine 14	AP-M													16		16	
Clutter 2	CL-M				1						1	68	28			98	
Clutter 3	CL-M										40			38		78	
Clutter 1	CL-M					2										2	
N/A	Background False Alarms	15	1		16	2			11	3	52		81	147	11	339	
<b>Total</b>		65	21	22	27	7	16	16	27	35	93	13	150	190	54	764	

**Table D-2. Results of Geophex Mine and Clutter Declaration Target Identification**

Truth	Type	Mine and Clutter Declarations															Total
		Mine 1	Mine 2	Mine 3	Mine 4	Mine 5	Mine 6	Mine 7	Mine 8	Mine 9	Mine 10	Mine 11	Mine 12	Mine 13	Mine 14	SIM	
Mine 1	AP-LM	37		1	2								2		3	45	
Mine 2	AT-M		19	4								1				24	
Mine 3	AP-M	1		15												16	
Mine 4	AT-LM				3								3			6	
Mine 5	AP-LM	4				1							2		9	16	
Mine 6	AP-M						16									16	
Mine 7	AT-M							16								16	
Mine 8	AT-LM								20							20	
Mine 9	AP-LM									31		1				32	
Mine 10	AP-LM	9			2	2									1	14	
Mine 11	AP-M		1	2								13				16	
Mine 12	AT-LM				8								2	7		17	
Mine 13	AT-LM	2			5								1	11	5	24	
Mine 14	AP-M														16	16	
Clutter 2	CL-M				3	1					1		81	48		134	
Clutter 3	CL-M								2	1	105			1	68	177	
Clutter 1	CL-M	17				31									135	183	
N/A	Background False Alarms	31	1		137	15			128	31	85		154	368	9	21	980
<b>Total</b>		101	21	22	160	50	16	16	150	63	191	13	240	442	228	39	1752



## APPENDIX E—METEOROLOGICAL DATA

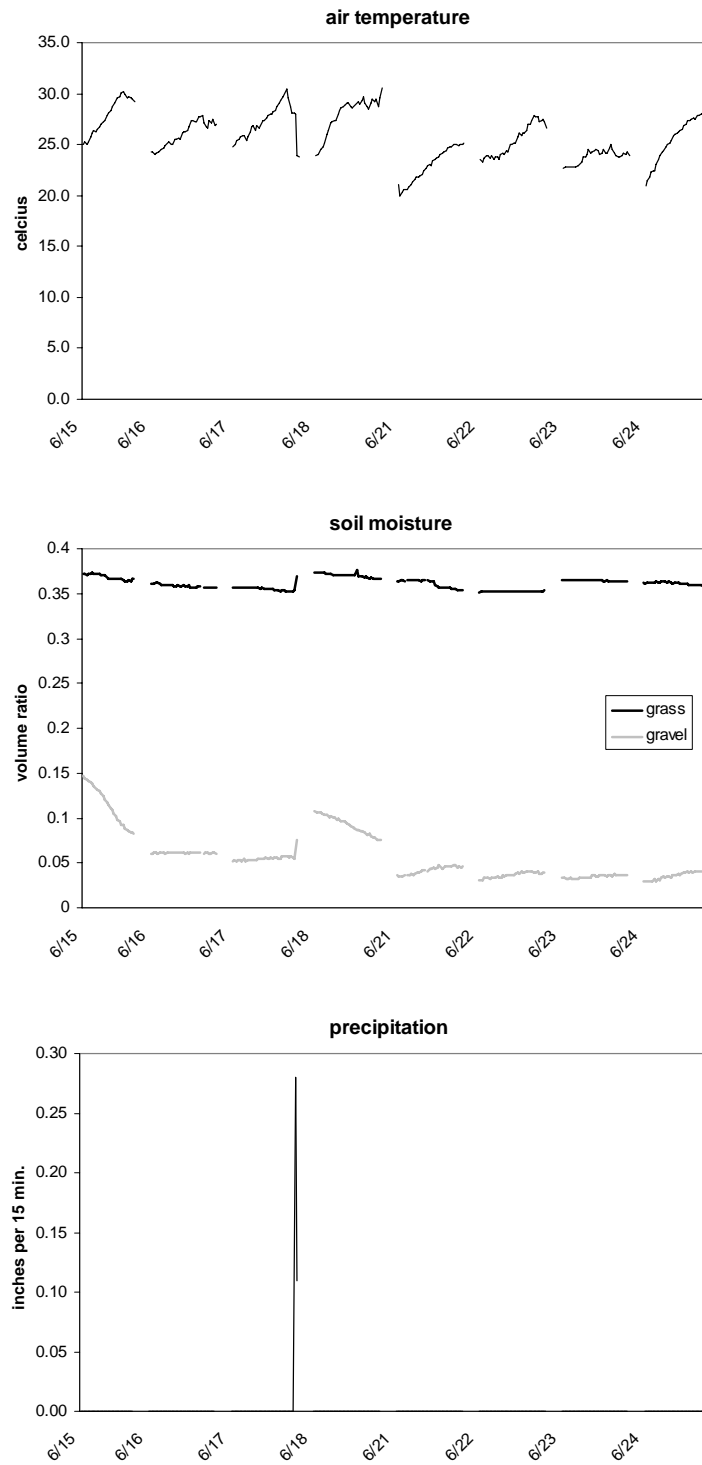


Figure E-1. Temperature, Soil Moisture, and Precipitation Data for the Test Period June 15–24, 2004