Analysis of GEM-3 Data Collected for the Advanced UXO Detection/Discrimination Technology Demonstration - U.S. Army Jefferson Proving Ground, Madison, Indiana

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ABSTRACT

This paper analyzes the UXO classification capabilities of the GEM-3 system using data collected for the Advanced UXO Detection/Discrimination Technology Demonstration at the U.S. Army Jefferson Proving Ground (JPG), Madison, Indiana. The approach taken in the analysis was to extract data points collected near each of the actual target locations and compare them to the calibration data acquired with known targets at the beginning of the demonstration. This was done to determine how well the data collected near each actual target matched the calibration signatures for the same ordnance type and the extent to which the data could be differentiated from other ordnance types and non-ordnance clutter. The targets were classified using a simple template-matching algorithm. This procedure resulted in an exact classification match for nearly half of the targets for which calibration data were available and a match to a similarly sized target for more than two-thirds of the medium and large targets. The sensor coverage of the test areas and the effect of test parameters such as ordnance size and depth on classification performance were also examined. New data were acquired with the GEM-3 to investigate the statistical variability of the instrument.

Keywords: Target Discrimination, UXO, Signatures, Spectroscopy, Electromagnetic Induction Spectroscopy

1. INTRODUCTION

This report documents analysis of GEM-3 data collected for the Advanced UXO Detection/Discrimination Technology Demonstration at the U.S. Army Jefferson Proving Ground (JPG), Madison, Indiana. The analysis was conducted by the ERDC and was funded through the 62720A/AF25 Program "301U-Subsurface UXO Detection and Discrimination" for Project "UXO03-Advanced Sensor Data Analysis Techniques for Improved Buried Target Detection." This post-demonstration analysis focuses on the evaluation of the stability of the data collected and improvements in target detection/discrimination.

The stability of the system is evaluated through statistical measurements of data collected during the technology demonstration. Based on findings of the characteristics of the collected data and initial work performed on target detection/discrimination[1], target detection/discrimination techniques are applied and evaluated.

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1.1 Test Site Description

The JPG test site consisted of three areas referred to as Areas 1, 2, and 3.[2] Each area is 1 hectare in size and contains known targets and clutter items. The naming convention for items in the test site is the area number followed by a hyphen and the item number (i.e. item number 43 in area 3 is 3-43, item number 48 in area 2 is 2-48). The location of the item is in UTM zone 16 NAD 83 coordinate system.[3] The depth of the item is measured from the top of the item to the ground surface. The UXO type, length, width, thickness, weight, azimuth, and inclination are recorded for each item. The inclination is oriented such that a value of +90 degrees corresponds to a nose-up position and the nose-down position is indicated by a value of –90 degrees.

1.2 Description of Data Collection Equipment

GEM-3 is a multi-frequency, frequency domain electromagnetic (FDEM) system.[4,5] The collection of multi-frequency FDEM data allows for Electromagnetic Induction Spectroscopy (EMIS) of the targets and background materials.[6] The EMIS signatures are characteristic of the objects' geometry and material composition and consist of complex (in-phase and quadrature) frequency responses. These EMIS signatures can provide a method to discriminate targets from natural and manmade clutter background materials. The frequencies used during the data collection were 90, 150, 330, 930, 2790, 8190, and 20010 Hz. The system has been developed by Geophex Ltd. with improvements funded by the Army's SBIR Phase II program (Contract DACA39-99-C-0001) and was operated by Geophex during the JPG technology demonstration. Geophex performed the initial target detection. The initial target discrimination was performed by AETC Inc.

2. ANALYSIS PROCEDURE

The target classification procedure performed on the JPG data by AETC for Geophex is based on estimating dipole model parameters from a number of GEM-3 measurements around a suspected target location[2]. While this classification procedure had worked well during previous demonstrations,[1] it did not work as well at JPG. Geophex correctly classified 25.8 percent (24/93) of the UXO items in the demonstration. A correct classification indicates that the object was identified correctly as the specific size and type of ordnance. Over half (48/93) of the targets were classified as non-ordnance clutter. The GEM-3 data from the JPG demonstration were analyzed by ERDC personnel to identify possible problems or limitations of the GEM-3 and to recommend where improvements might be made.

2.1 Approach

The approach taken in the ERDC analysis of the performance of the GEM-3 at JPG was to extract data points collected near each of the actual target locations and compare them to the calibration data acquired with known targets at the beginning of the demonstration. Throughout this report, the term "data point" refers to a GEM-3 measurement consisting of both the in-phase and quadrature measurements for each of the seven frequencies for which data were collected during the JPG demonstration. The seven frequencies used were 90, 150, 330, 930, 2790, 8190, and 20010 Hz. A computer program was developed to extract the data points and analyze the background signature for the set of data points near each target. A second computer program was developed to compare the extracted data points with calibration signatures. This was done to determine how well the data collected near each actual target matched the calibration signatures for the same ordnance type and the extent to which the data could be differentiated from other ordnance types. In addition, data points near all the objects declared by Geophex were compared with the calibration signatures to determine the degree of confusion caused by non-ordnance clutter. In addition to the analysis of the JPG data, new measurements were made with the GEM-3 for several minutes over a target area to determine the statistical variability of the instrument.

2.2 Extraction of Data Points

Due to the size of the data sets that were acquired for each test area at JPG, it was necessary to develop a way to extract the relevant data for analysis. A graphical user interface, GridScan, was written to allow the user to extract the data near a given GPS coordinate for analysis. GridScan reads in a list of targets and their location, and extracts the data within a user-defined box about the item for analysis. The list of points consists of either the GPS locations given by Geophex or the GPS locations in the ground truth.

Background variability in the data set adds uncertainty or error to the target signature and this degrades the viability of classification algorithms. To minimize the effect of background variability, the background is subtracted from the data. For the purpose of this investigation the target data were defined as the points within a 1-m box centered on each target, and these data were extracted for classification analysis. The background data were defined as the data within a 5-m box about the target excluding the 1-m target data set. To determine the best background value to subtract from the target, a histogram of the values in the background was created. Then, the centroid of the largest peak in that set was chosen as the background value.

2.3 Analysis of Data Points

2.3.1 Calibration data

While at the site, Geophex acquired the calibration data by passing the GEM-3 over each type of ordnance placed in an open trench, as shown in Figure 1. Because of sensor problems at the site, the available calibration data were very limited. No calibration data were available for the 76-mm, 105-mm, and 5-inch projectiles. For the other ordnance types, data were collected with inclination angles of 0, 90 (nose up), and –90 (nose down) deg. Because the actual targets were buried with many different inclination angles and the inclination angle has a significant influence on the signature of the target, data were interpolated between these three measurements at 5-deg increments. Data were collected at multiple depths for some ordnance types but not for others. Because depth appears to affect only the magnitude of the data and not the shape of the curves, the data at the shallowest depth for each ordnance type were selected for analysis in order to simplify the process.

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Figure 1. Acquisition of calibration data with the GEM-3

2.3.2 Error in fit

A simple measure of the error in fit between a data point and a calibration signature was used. The error in fit was calculated separately for the in-phase and quadrature and then summed to get a single measure. The in-phase measurements for each data point were normalized by multiplying each frequency measurement by the ratio of the sum of the in-phase responses of the data point for all frequencies and the sum of the in-phase responses of the calibration signature for all frequencies. The quadrature measurements for each data point were normalized in an analogous manner. Once the measurements were normalized, the error in fit, E, was calculated by

$$E = \frac{\sqrt{\sum_{k=1}^{k=7}(CI_k - PI_k)^2}}{\sum_{k=1}^{k=7}|CI_k|} + \frac{\sqrt{\sum_{k=1}^{k=7}(CQ_k - PQ_k)^2}}{\sum_{k=1}^{k=7}|CQ_k|} \qquad (1)$$

where CI_k is the calibration in-phase response and PI_k is the data point in-phase response at frequency k. CQ_k and PQ_k are the calibration and data point quadrature responses, respectively, at frequency k.

2.3.3 Analysis program

A graphical user interface computer program was developed to automate the process of comparing data points with calibration signatures under various conditions. The program displays one line for each data point near the selected object, the total in phase and quadrature magnitude, the distance from the target if the object is a known target, and information about the three closest matches of the point with calibration data. The information for each match consists of the ordnance type, depth, and inclination and the error between the data point and the calibration signature. The in-phase and quadrature data for the selected data point and for the calibration data are also displayed for comparison. Calibration data are displayed for either the best matching ordnance or the actual ordnance corresponding to the current Target ID, depending on the operator's selection. The positions of the data points around the actual target location are also displayed. The actual target is shown at the origin in red. Points with match errors greater than the current ordnance/non-ordnance threshold are shown in black. Points with errors less than the threshold, but greater than two-thirds of the threshold, are shown in dark blue. Points with errors between one-third and two-thirds of the threshold are shown in cyan. Points with errors below one-third of the threshold are displayed in yellow. The currently displayed data point is shown as a diamond rather than a plus. An operator can also select individual frequencies to be excluded from calculations through the graphical user interface.

3. RESULTS

3.1 Area Coverage

Complete area coverage is essential for determining the performance of a UXO detection system. Table 1 shows the number of data points within a 1-m box centered on each target and the distance from the target of the closest point. No target is identified for which measurements were not taken within 1-meter.

Table 1
Proximity of GEM-3 Data Points to Targets at JPG

Target ID	Number of Points	Closest Point (m)	Target ID	Number of Points	Closest Point (m)	Target ID	Number of Points	Closest Point (m)
1-86	8	0.1845	1-138	9	0.2583	2-148	8	0.2552
1-88	12	0.1163	1-140	9	0.2118	2-150	11	0.078
1-90	15	0.1084	1-142	8	0.1012	2-152	10	0.1217
1-92	11	0.2047	1-144	8	0.0221	2-154	11	0.1662
1-94	5	0.3789	1-146	14	0.1985	2-156	10	0.094
1-96	10	0.254	1-147	6	0.1779	2-158	9	0.1112
1-98	8	0.0524	1-148	8	0.1818	2-160	9	0.1
1-100	7	0.1802	1-149	8	0.159	2-161	7	0.1206
1-102	7	0.037	1-150	40	0.0716	2-162	10	0.3109
1-104	7	0.0226	1-151	9	0.1703	2-164	4	0.0481
1-106	8	0.2547	1-152	9	0.2302	2-166	4	0.1448
1-108	8	0.1743	1-153	9	0.0804	3-68	10	0.099
1-112	9	0.2053	2-112	3	0.3122	3-70	9	0.312
1-113	8	0.1205	2-114	8	0.3113	3-72	10	0.1537
1-114	11	0.1056	2-116	8	0.2823	3-74	10	0.1845
1-115	8	0.2459	2-118	9	0.1788	3-76	4	0.2053
1-116	6	0.3548	2-120	8	0.2594	3-78	9	0.2821
1-117	18	0.1302	2-122	10	0.1062	3-80	13	0.1604
1-118	10	0.0977	2-124	8	0.063	3-82	7	0.2288
1-119	12	0.0546	2-126	7	0.2474	3-84	9	0.126
1-120	7	0.2299	2-128	8	0.2001	3-86	8	0.3152
1-121	9	0.0663	2-130	10	0.3674	3-88	5	0.0757
1-122	5	0.0944	2-131	7	0.2354	3-90	9	0.1502
1-123	10	0.1379	2-132	5	0.1081	3-92	6	0.0715
1-124	31	0.0136	2-134	8	0.0648	3-94	8	0.2611
1-126	10	0.1342	2-136	8	0.1592	3-96	8	0.2901
1-128	11	0.0224	2-138	7	0.4204	3-98	11	0.0272
1-130	8	0.0774	2-140	8	0.1918	3-100	10	0.058
1-132	9	0.305	2-142	11	0.1674	3-102	8	0.1774
1-134	10	0.0854	2-144	7	0.3494	3-104	12	0.124
1-136	5	0.144	2-146	18	0.1793	3-106	11	0.1329

3.2 Data Variability

In order to determine the precision of the instrument, an experiment was set up at the ERDC to collect a statistically significant number of measurements for a fixed source. GEM-3 was placed in a wooden rack 10 cm above the ground, and first data were collected in remote mode using a 233-MHz Pentium II computer. The Geophex data display program was used to collect the data, but anomalies in the data were observed.

At irregular intervals, obviously corrupted data were plotted to the screen. Initial examination of the collected data showed that there were shifts in the data stream. Geophex advised that a 500-MHz machine was required to use this software, so more data were collected in "survey mode". Table 2 shows the statistical analysis of approximately 45 min of data that were collected to make histograms for three separate cases background, a 20-mm projectile and a 57-mm mortar.

3.3 Comparison of Data Points with Calibration Data

To determine how closely the data points acquired near targets during the demonstration match the corresponding calibration signatures, the data points within a 1-m box centered on each target were extracted and compared to the calibration signature for the same ordnance type as the target at all inclination angles and the best matching angle was selected. The exact inclination angle of the target was not used because the position of the sensor relative to the target during the demonstration varied from point to point, unlike the calibration data, where the sensor was always directly above the target. Tables 3, 4, and 5 summarize the results of this comparison. Targets for which no calibration data were available are not included.

Table 2
Statistical Information on Fixed Target Variation
Sample Size N=15,480

Description	Component	Frequency	Mean	Std. Deviation
Background	Inphase1	90	0.0342	0.15307
	Inphase2	150	0.0179	0.091938
	Inphase3	330	0.0213	0.04845
	Inphase4	930	0.0331	0.03764
	Inphase5	2,790	0.0922	0.07864
	Inphase6	8,190	0.3074	0.25669
	Inphase7	20,010	-3.3078	2.14604
	Quad1	90	0.0137	0.15560
	Quad2	150	-.0000155	0.09292
	Quad3	330	-.00406	0.04263
	Quad4	930	0.0057	0.03581
	Quad5	2,790	-0.0158	0.13205
	Quad6	8,190	-0.8627	0.94256
	Quad7	20,010	-8.6170	6.78427
20 mm	Inphase1	90	-78.5324	6.7391
	Inphase2	150	-75.8057	6.5315
	Inphase3	330	-69.5563	6.3570
	Inphase4	930	-57.7184	6.1737
	Inphase5	2,790	-41.1624	6.0193
	Inphase6	8,190	-34.5964	6.0938
	Inphase7	20,010	-90.0381	8.0931
	Quad1	90	7.4923	1.5388
	Quad2	150	9.9834	0.7586
	Quad3	330	13.9623	0.4118
	Quad4	930	18.4170	0.3942
	Quad5	2,790	18.1551	0.6143
	Quad6	8,190	4.0144	1.1135
	Quad7	20,010	-15.8804	1.8402
57 mm	Inphase1	90	-1782.262	21.3220
	Inphase2	150	-1645.632	20.5687
	Inphase3	330	-1379.235	19.2048
	Inphase4	930	-920.9837	16.5396
	Inphase5	2,790	-325.7171	12.0936
	Inphase6	8,190	23.4787	6.8598
	Inphase7	20,010	550.8331	4.1577
	Quad1	90	365.1280	2.8266
	Quad2	150	448.8472	2.5750
	Quad3	330	578.9956	3.4596
	Quad4	930	718.6377	5.2193
	Quad5	2,790	782.9586	7.1893
	Quad6	8,190	698.6334	8.3765
	Quad7	20,010	551.8812	8.8383

Table 3
Comparison of Data Points with Calibration Signatures in Area 1

Target ID	Type	Depth (cm)	Inclination angle	**Number of Points**	**Minimum Error**	Maximum Error	Mean Error	Std Dev of Error
1-86	4.2in	20	45	8	0.0100	0.1095	0.0491	0.0361
1-88	60mm	35	0	12	0.0235	0.6212	0.1954	0.1850
1-90	4.2in	35	0	15	0.0165	0.4299	0.0968	0.1209
1-92	81mm	20	20	11	0.0425	0.2417	0.0873	0.0592
1-94	81mm	25	55	5	0.0890	0.3049	0.1846	0.0785
1-96	81mm	15	35	10	0.0095	0.3622	0.0803	0.1099
1-98	60mm	10	20	8	0.0097	0.1492	0.0574	0.0483
1-100	60mm	20	30	7	0.0239	0.4182	0.2251	0.1611
1-102	81mm	25	45	7	0.0084	0.2707	0.0865	0.0902
1-104	81mm	35	0	7	0.0299	0.1377	0.0709	0.0404
1-106	60mm	25	35	8	0.0513	0.2855	0.1362	0.0702
1-108	60mm	20	45	8	0.0258	0.5122	0.2734	0.1695
1-112	20mm	10	10	9	0.1090	0.3726	0.2028	0.0860
1-114	20mm	15	20	11	0.2824	0.5345	0.3857	0.0841
1-116	20mm	15	0	6	0.2400	0.5572	0.4014	0.1324
1-117	152mm	90	45	18	0.0760	0.6827	0.2678	0.1644
1-119	152mm	40	30	12	0.0224	0.1922	0.0996	0.0508
1-121	155mm	50	0	9	0.0119	0.1403	0.0391	0.0390
1-123	20mm	0	90	10	0.1027	0.4538	0.2964	0.1240
1-124	20mm	0	-90	31	0.2523	0.6976	0.3938	0.1128
1-126	57mm	20	30	10	0.2184	0.6329	0.5026	0.1241
1-128	20mm	10	0	11	0.0438	0.2624	0.1512	0.0799
1-132	57mm	25	0	9	0.0247	0.4117	0.1392	0.1157
1-134	20mm	5	30	10	0.0758	0.6445	0.4085	0.1999
1-136	155mm	50	75	5	0.0267	0.0686	0.0487	0.0158
1-138	57mm	15	45	9	0.0302	0.2422	0.1038	0.0813
1-140	20mm	5	15	9	0.1186	0.467	0.2615	0.1275
1-142	57mm	15	45	8	0.0058	0.038	0.0235	0.0119
1-146	20mm	5	0	14	0.1084	0.5391	0.3326	0.1517
1-147	57mm	25	0	6	0.0114	0.4985	0.2442	0.2105
1-148	20mm	10	45	8	0.1830	0.6268	0.3457	0.1805
1-149	2.75in	50	55	8	0.0160	0.2399	0.1055	0.0726
1-150	2.75in	70	45	40	0.0357	0.5201	0.1944	0.1025
1-152	2.75in	15	0	9	0.0458	0.109	0.0772	0.0243
1-153	2.75in	76	90	9	0.0767	0.6012	0.4352	0.1697

Table 4
Comparison of Data Points with Calibration Signatures in Area 2

Target ID	Type	Depth (cm)	Inclination angle	**Number of Points**	**Minimum Error**	Maximum Error	Mean Error	Std Dev of Error
2-112	81mm	10	90	3	0.0096	0.0643	0.0289	0.0307
2-114	81mm	20	-90	8	0.0070	0.2249	0.0690	0.0684
2-116	81mm	30	0	8	0.0122	0.1463	0.0606	0.0463
2-118	60mm	35	45	9	0.1200	0.5099	0.2611	0.1142
2-120	60mm	30	0	8	0.0424	0.3254	0.1130	0.0932
2-122	60mm	10	30	10	0.0232	0.5161	0.1351	0.1592
2-124	60mm	20	10	8	0.0188	0.6151	0.1506	0.2004
2-126	81mm	35	45	7	0.0274	0.1084	0.0570	0.0323
2-128	60mm	10	20	8	0.0046	0.0888	0.0364	0.0279
2-130	81mm	20	0	10	0.0159	0.3097	0.0759	0.0882
2-131	81mm	25	0	7	0.0057	0.0379	0.0200	0.0115
2-134	4.2in	40	0	8	0.0118	0.0377	0.0257	0.0112
2-136	20mm	5	10	8	0.2054	0.6724	0.4012	0.1689
2-138	20mm	5	15	7	0.2121	0.5602	0.3455	0.1183
2-142	152mm	91	45	11	0.1341	0.3596	0.2438	0.0717
2-144	152mm	45	30	7	0.0642	0.3177	0.1472	0.1082
2-146	20mm	0	90	18	0.0610	0.6574	0.3535	0.1625
2-148	20mm	0	-90	8	0.1893	0.6583	0.4192	0.1874
2-150	20mm	10	0	11	0.0284	0.6097	0.3680	0.1845
2-152	57mm	25	0	10	0.0224	0.2997	0.1039	0.0993
2-154	57mm	20	45	11	0.0252	0.2989	0.1201	0.0891
2-156	155mm	102	90	10	0.0843	0.5366	0.1896	0.1412
2-158	20mm	10	20	9	0.0276	0.5122	0.1775	0.1465
2-160	57mm	35	40	9	0.0285	0.5212	0.2257	0.1471
2-161	155mm	75	30	7	0.0215	0.1410	0.0649	0.0430
2-164	2.75in	60	10	4	0.0660	0.1433	0.1047	0.0316
2-166	2.75in	75	20	4	0.2687	0.5892	0.4617	0.1464

Table 5
Comparison of Data Points with Calibration Signatures in Area 3

Target ID	Type	Depth (cm)	Inclination angle	**Number of Points**	**Minimum Error**	Maximum Error	Mean Error	Std Dev of Error
3-68	60mm	20	90	10	0.0149	0.3716	0.1308	0.1373
3-70	81mm	25	0	9	0.0158	0.0521	0.0301	0.0138
3-72	60mm	25	30	10	0.0202	0.4133	0.2271	0.1573
3-74	60mm	30	45	10	0.0152	0.0884	0.0390	0.0231
3-76	81mm	20	-90	4	0.0065	0.0454	0.0261	0.0185
3-78	60mm	35	40	9	0.0213	0.4177	0.1242	0.1205
3-80	81mm	25	0	11	0.0111	0.1795	0.0350	0.0503
3-82	60mm	20	15	7	0.0181	0.3424	0.1001	0.1114
3-84	81mm	25	0	9	0.1225	0.1694	0.1452	0.0137
3-86	20mm	1	90	8	0.1028	0.3071	0.1919	0.0804
3-88	20mm	1	0	5	0.0545	0.4379	0.1992	0.1542
3-90	20mm	15	0	9	0.0732	0.5454	0.2431	0.1550
3-92	20mm	15	30	6	0.0622	0.5500	0.2650	0.1949
3-94	57mm	35	0	8	0.0462	0.2992	0.1548	0.0933
3-96	57mm	25	20	8	0.0185	0.3410	0.0764	0.1088
3-100	152mm	91	35	10	0.1582	0.4296	0.2549	0.0835
3-102	155mm	120	20	8	0.2182	0.5247	0.3507	0.1185
3-106	2.75in	50	30	11	0.0562	0.4900	0.2228	0.1468

3.3.1 Strong signatures

The minimum error columns of Tables 3, 4, and 5 show the error in fit of the data point near the target that most closely matches the calibration signature for the ordnance type of the target. Figures 2 through 9 show examples of data points near targets of each of the different ordnance types that closely match the corresponding calibration signatures.

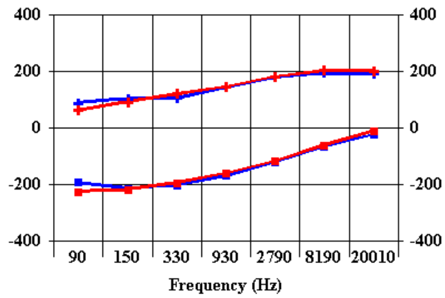

Figure 2. Best matching point for target 2-158 (20-mm projectile)

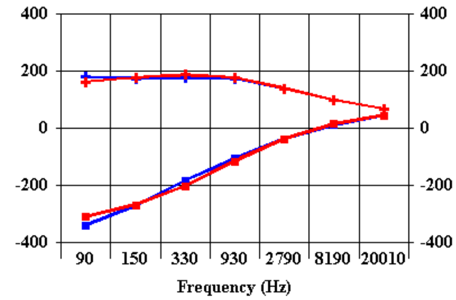

Figure 3. Best matching point for target 3-96 (57-mm mortar)

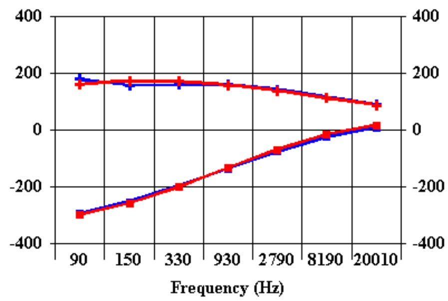

Figure 4. Best matching point for target 3-74 (60-mm mortar)

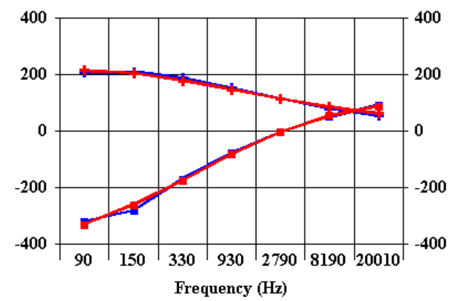

Figure 5. Best matching point for target 1-149 (2.75-inch rocket)

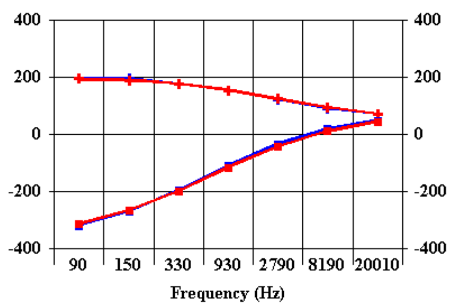

Figure 6. Best matching point for target 1-96 (81-mm mortar)

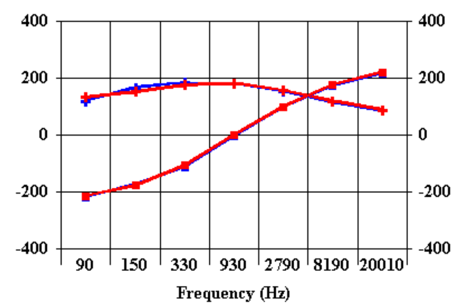

Figure 7. Best matching point for target 2-134 (4.2-inch mortar)

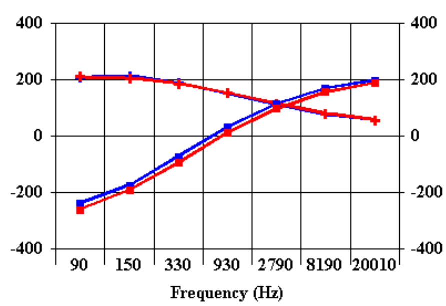

Figure 8. Best matching point for target 1-119 (152-mm projectile)

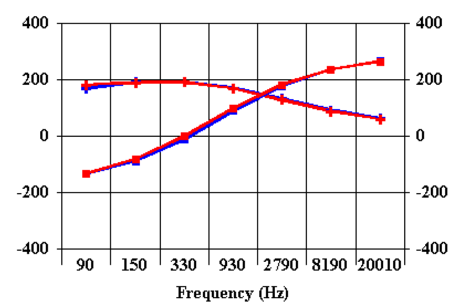

Figure 9. Best matching point for target 1-121 (155-mm projectile)

3.3.2 Weak signatures

A total of 19 targets had no points near them with an error in fit less than 0.1. Twelve of these targets were 20-mm projectiles and the weak signatures were likely due to the small size of the target. The few data points with good signatures near 20-mm projectiles were very close to the target (within 0.25 m). Targets 2-150 and 2-158 are examples of 20-mm targets that had data points with good signatures very near the target. In some cases, the sensor did not get that close to a target. However, even when the sensor did get very close to a 20-mm projectile, the signature was not necessarily strong enough to classify it correctly. Target 1-124, with a total of 12 data points within 0.25 m, but none with a good signature, is a good example of this.

Figures 10 through 16 show the best matching data points for the seven larger targets that had no points with error in fit less than 0.1. All but two of these targets, 3-84 and 1-126, were among the deepest targets of their type emplaced at JPG and their weak signatures are probably due largely to their depth. The in-phase data for target 3-84 consists of large magnitude values of a nearly constant value for every frequency, possibly due to a recording error of some kind. Figure 10 shows that the quadrature data for the target matches the calibration data very well. The data points for target 1-126, a 57-mm mortar at a depth of 20 cm, had an average total magnitude of only 62, a much weaker signal than similar targets at similar depths. The total magnitude of a data point is the sum of the absolute values of the in-phase and quadrature measurements for all frequencies.

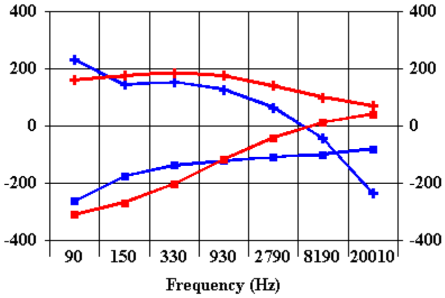

Figure 10. Best matching point for target 1-126 (57-mm mortar)

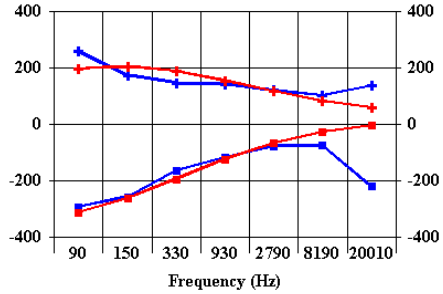

Figure 11. Best matching point for target 2-118 (60-mm mortar)

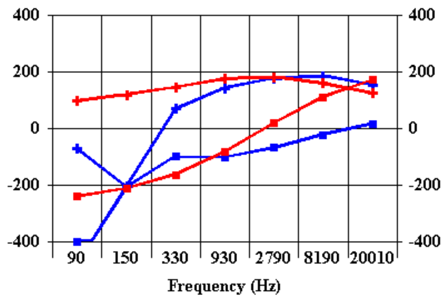

Figure 12. Best matching point for target 2-166 (2.75-inch rocket)

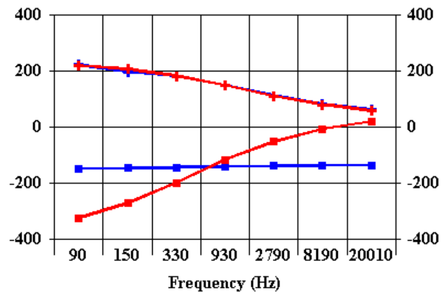

Figure 13. Best matching point for target 3-84 (81-mm mortar)

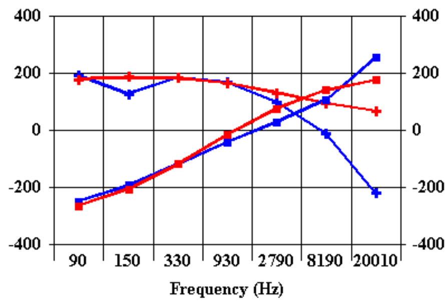

Figure 14. Best matching point for target 3-100 (152-mm projectile)

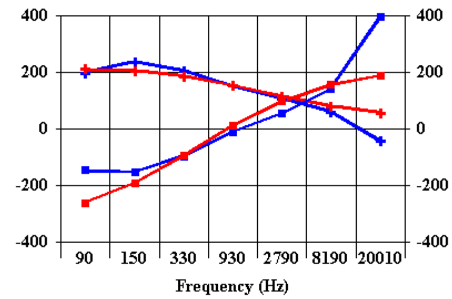

Figure 15. Best matching point for target 2-142 (152-mm projectile)

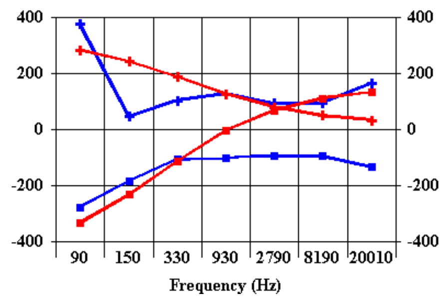

Figure 16. Best matching point for target 3-102 (155-mm projectile)

3.3.3 Depth effects

The effect of depth on the signal strength of the GEM-3 is apparent in Figure 17, which shows the average total magnitude of data points within a 1-m box centered on the target versus target depth for the 155-mm projectiles, 81-mm mortars, and 60-mm mortars emplaced at JPG. The total magnitude of a data point is the sum of the absolute values of the in-phase and quadrature measurements for all frequencies. For all three ordnance types, the signal strength decreases sharply with increasing depth. The effect of target depth on the classification of targets can best be illustrated by examining the data for the 155-mm projectiles, which were the largest targets in the demonstration. A total of five 155-mm projectiles were included in the demonstration at depths of 50, 75, 102, and 120 cm. The data points near the two 155-mm projectiles buried at 50 cm, (1-121 and 1-136) had an average total magnitude of over 2000, and nearly all of them match the calibration signatures quite well. The points near target 2-161, buried at 75 cm, have an average magnitude of 396 and also match the calibration signatures well. The data points near the two deepest 155-mm projectiles (2-156 and 3-102) have an average magnitude of less than 200. The deepest (3-102) has no points with a recognizable signature. Target 2-156 has three points that match the calibration signature for a 155-mm projectile with an error just under 0.1, although they match other ordnance types slightly better. From these data, it appears that reliable classification of 155-mm projectiles at depths greater than 1 m is unlikely. Classification of smaller ordnance types will suffer from weak signals at shallower depths. Other targets that produced weak signatures due to depth include three 152-mm projectiles (1-117, 2-142, and 3-100) all at depths of approximately 90 cm and two 2.75-inch rockets (1-153 and 2-166) both at depths of 76 cm. Three targets [2-132 (5-inch projectile at a depth of 91 cm), 2-140 (105-mm projectile at a depth of 70 cm), and 3-104 (76-mm projectile at a depth of 76 cm)] for which there was no calibration data also appeared to be too deep for classification. Targets of these types at shallower depths were classified as targets of similar size for which calibration data were available.

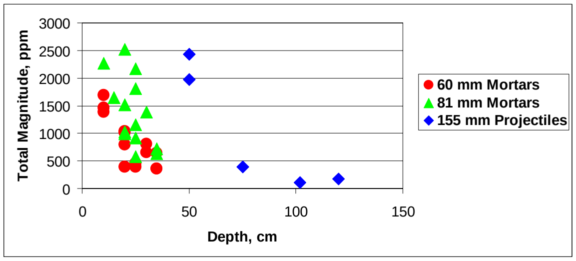

Figure 17. Average total magnitude versus. depth for selected ordnance types

3.3.4 Errors by frequency

For many data points, the error in fit with the calibration data was dominated by the measurement for a single frequency. In such cases, excluding that frequency from the calculations produced a much closer fit of the point with the calibration data. An example of this is shown in Figures 18 and 19. The 90-Hz data are included in the graph in Figure 19 for reference, but were not included in the magnitude normalization or error calculations. Using all frequencies, as shown in Figure 18, the error in fit was calculated to be 0.1369, while excluding the 90-Hz data reduced the error to only 0.0645.

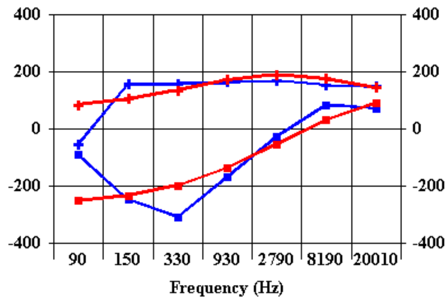

Figure 18. Calibration match with all frequencies for target 1-132 (57 mm mortar)

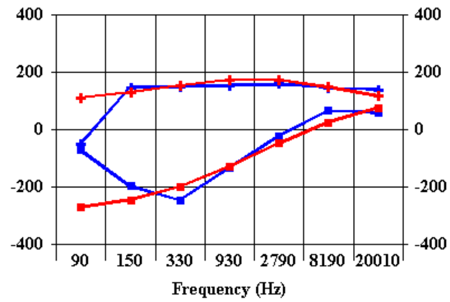

Figure 19. Calibration match without 90 Hz for target 1-132 (57 mm mortar)

Although 90-Hz was the most likely frequency to cause problems, it was not the only one that did. The errors in fit of the data points shown in a previous section for targets 2-118, 2-142, and 3-100 are dominated by the 20010-Hz measurement. Excluding that frequency brings the error in fit for all three data points to less than 0.08. In almost all cases, data points with large errors in one frequency were relatively low in magnitude.

To determine the overall contributions of particular frequencies to the error between data points and calibration signatures throughout the data set, the differences between all the data points and corresponding calibration signatures for each frequency were averaged. The results are shown in Figure 20. The lowest frequency, 90 Hz, has a substantially larger average difference than the other frequencies.

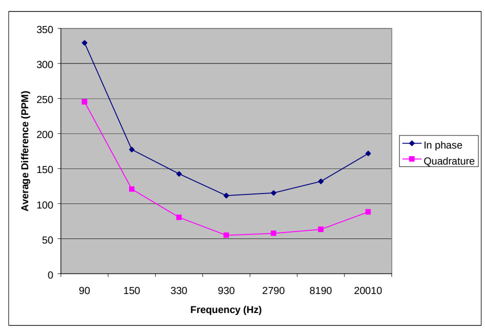

Figure 20. Average difference by frequency

3.4 Classification of Targets

Figures 21, 22, and 23 show the calibration data for all the different ordnance types at 0, 90, and –90 deg, respectively. The data have been normalized to the same total quadrature and the same total in-phase responses so that the relative responses of each ordnance type at each of the seven frequencies can be compared. Some of the ordnance types have signatures very similar to each other. A simple classification procedure was applied to the JPG data to examine the separability of the different ordnance types from each other. Each target was classified using the single data point with the greatest magnitude of the points near the target. The error in fit between the data point and each ordnance type at each inclination angle was calculated. The target was classified as the ordnance type that had the lowest error in fit at any inclination angle. The results are shown in Table 6. Overall, 41.9 percent (39/93) of the targets were classified correctly. Excluding the three ordnance types for which no calibration data was available, 48.8 percent (39/80) of the targets were correctly classified, including 60.1 percent (20/33) of the mortars, 40.0 percent (16/40) of the projectiles, and 42.9 percent (3/7) of the rockets. Because of the very similar signatures of some of the targets, a more informative way to look at the classification matrix would be to group the targets by size as shown in Table 7. At least 71.0 percent (66/93) of the targets are classified in the correct group, including 78.1 percent (56/73) of the medium and large targets.

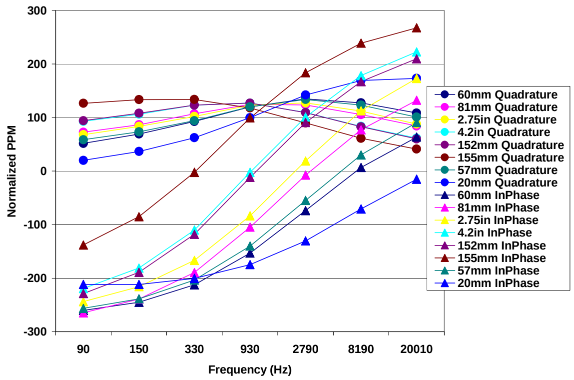

Figure 21. Calibration data with targets at 0 deg inclination

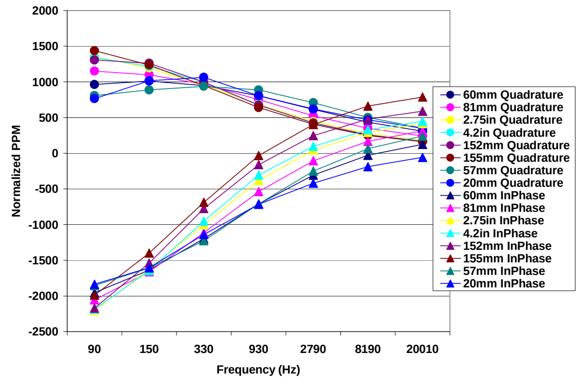

Figure 22. Calibration data with targets at 90 deg inclination (nose up)

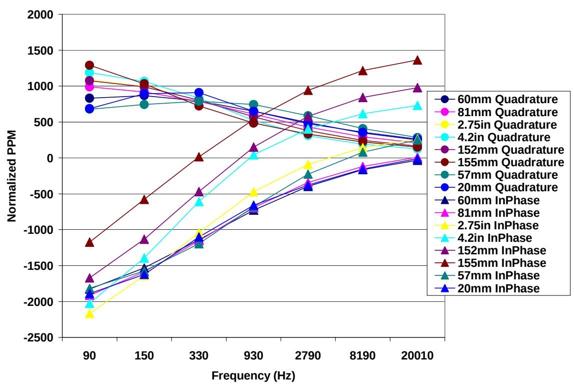

Figure 23. Calibration data with targets at –90 deg inclination (nose down)

Table 6
Classification Matrix Using All Frequencies

	Ordnance Type												
Classification	20mm	57mm	60mm	2.75in	76mm	81mm	105mm	4.2in	5.0in	152mm	155mm	FA	Total
20mm	9	1	3	2	0	0	0	0	0	0	0	0	15
57mm	1	4	2	0	0	3	0	0	0	0	0	0	10
60mm	3	3	8	2	0	1	0	0	0	0	1	0	18
2.75in	4	0	0	3	1	2	0	0	0	1	1	0	12
76mm	0	0	0	0	0	0	0	0	0	0	0	0	0
81mm	0	1	1	0	1	9	1	0	0	1	0	0	14
105mm	0	0	0	0	0	0	0	0	0	0	0	0	0
4.2in	0	0	0	0	1	0	0	3	0	0	0	0	4
5.0in	0	0	0	0	0	0	0	0	0	0	0	0	0
152mm	0	1	0	0	0	0	0	0	1	0	0	0	2
155mm	3	0	1	0	2	0	3	0	3	3	3	0	18
Total	20	10	15	7	5	15	4	3	4	5	5	0	93
%classified	45.0	40.0	53.3	42.9	0.0	60.0	0.0	100.0	0.0	0.0	60.0		

Table 7
Classification Matrix Using All Frequencies
Aggregated by Ordnance Size

Classification	**20mm**	**57-81mm**	**105-155mm**
20mm	9	6	0
57-81mm	8	41	5
105-155mm	3	5	16
Total	20	52	21
% classified	45.0	78.8	76.2

Because of the larger average difference between the data points and the calibration data for the 90-Hz data, that frequency was excluded from the calculations to see if the results would improve. The results did not change significantly in either of these classifications compared with the classification using all frequencies. A total of 40 targets were classified correctly in each of them, one more than were classified correctly using all frequencies. Several targets changed classifications when the 90-Hz data were excluded, but the gains and losses essentially canceled each other out. Viewing the data for individual targets indicates that excluding the 90 Hz data reduces the errors of data points relative to the calibration data, particularly for data points with weak signals. This is as expected, given the greater noise level of the data acquired at that frequency. However, excluding some frequencies increases the potential for confusion between similar ordnance types.

3.5 Classification of All Detected Anomalies

The classifications in the preceding section involved only data points near actual targets; therefore, it demonstrates only the capability to separate different types of ordnance from each other given the presence of a target. However, in a realistic search scenario, real targets must be separated from clutter. To examine this aspect of classification with the

GEM-3, data points near all objects declared by Geophex were extracted and the classification procedure repeated. An ordnance/non-ordnance threshold was specified to separate targets from clutter. The results of this classification using all frequencies at three different threshold levels are given in Tables 8 through 13. At the lowest threshold value used (0.05) 23 of the 80 targets with calibration data were properly classified with 74 false alarms classified as ordnance. At a threshold of 0.1, 31 of the 80 targets were classified correctly with 155 false alarms classified as ordnance. At a threshold of 0.15, 38 of the 80 targets were correctly classified with 212 false alarms classified as ordnance. The biggest gains in the number of correctly classified targets as the threshold was raised were in the smaller ordnance categories, especially the 20-mm projectiles where the number correct went from 1 at the lowest threshold to 8 at the highest.

Table 8
Classification Matrix with Threshold of 0.05

	Ordnance Type											
Classification	20mm	57mm	60mm	2.75in	76mm	81mm	105mm	4.2in	5.0in	152mm	155mm	FA	Total
20mm	1	0	1	0	0	0	0	0	0	0	0	18	20
57mm	0	4	2	0	0	2	0	0	0	0	0	5	13
60mm	0	2	5	1	0	0	0	0	0	0	0	12	20
2.75in	1	0	0	0	1	0	0	0	0	0	0	12	14
76mm	0	0	0	0	0	0	0	0	0	0	0	0	0
81mm	0	1	1	0	1	8	0	0	0	0	0	13	24
105mm	0	0	0	0	0	0	0	0	0	0	0	0	0
4.2in	0	0	0	0	0	0	0	3	0	0	0	7	10
5.0in	0	0	0	0	0	0	0	0	0	0	0	0	0
152mm	0	0	0	0	1	0	0	0	1	0	0	5	7
155mm	0	0	0	0	0	0	1	0	0	0	2	2	5
Non-Ord	17	3	6	6	2	4	3	0	3	5	3	450	502
Total	19	10	15	7	5	14	4	3	4	5	5	524	615
%classified	5.3	40.0	33.3	0.0	0.0	57.1	0.0	100.0	0.0	0.0	40.0		

Table 9
Classification Matrix, Aggregated by Ordnance Size, with Threshold of 0.05

Classification	20mm	57-81mm	105-155mm	False Alarm
20mm	1	1	0	18
57-81mm	1	28	0	42
105-155mm	0	1	7	14
Non-Ordnance	17	21	14	450
Total	19	51	21	524
% classified	5.3	54.9	33.3	85.9

Table 10
Classification Matrix with Threshold of 0.1

	Ordnance Type											
Classification	20mm	57mm	60mm	2.75in	76mm	81mm	105mm	4.2in	5.0in	152mm	155mm	FA	Total
20mm	3	0	1	0	0	0	1	0	0	0	0	60	65
57mm	0	4	2	0	0	2	0	0	0	0	0	13	21
60mm	0	3	7	1	0	0	0	0	1	0	0	18	30
2.75in	2	0	0	1	1	0	0	0	0	0	0	20	24
76mm	0	0	0	0	0	0	0	0	0	0	0	0	0
81mm	0	2	1	0	1	10	0	0	0	0	0	17	31
105mm	0	0	0	0	0	0	0	0	0	0	0	0	0
4.2in	0	0	0	1	0	0	0	3	0	1	0	11	16
5.0in	0	0	0	0	0	0	0	0	0	0	0	0	0
152mm	0	0	0	0	1	0	0	0	1	0	0	6	8
155mm	0	0	0	0	0	0	2	0	0	2	3	10	17
Non-Ord	14	1	4	4	2	2	1	0	2	2	2	369	403
Total	19	10	15	7	5	14	4	3	4	5	5	524	615
%classified	15.8	40.0	46.7	14.3	0.0	71.4	0.0	100.0	0.0	0.0	60.0		

Table 11
Classification Matrix, Aggregated by Ordnance Size, with Threshold of 0.1

Classification	20mm	57-81mm	105-155mm	False Alarm
20mm	3	1	1	60
57-81mm	2	35	1	68
105-155mm	0	2	12	27
Non-Ordnance	14	13	7	369
Total	19	51	21	524
% classified	15.8	68.6	57.1	70.4

Table 12
Classification Matrix with Threshold of 0.15

	Ordnance Type											
Classification	20mm	57mm	60mm	2.75in	76mm	81mm	105mm	4.2in	5.0in	152mm	155mm	FA	Total
20mm	8	0	1	0	0	0	1	0	0	0	0	90	100
57mm	1	4	2	0	0	2	0	0	0	0	0	13	22
60mm	1	3	8	1	0	1	0	0	1	0	0	21	36
2.75in	2	1	0	2	1	1	0	0	0	0	0	24	31
76mm	0	0	0	0	0	0	0	0	0	0	0	0	0
81mm	0	2	1	0	1	10	0	0	0	1	0	20	35
105mm	0	0	0	0	0	0	0	0	0	0	0	0	0
4.2in	0	0	1	1	0	0	0	3	0	1	0	13	19
5.0in	0	0	0	0	0	0	0	0	0	0	0	0	0
152mm	0	0	0	0	1	0	0	0	1	0	0	7	9
155mm	0	0	0	0	1	0	2	0	1	2	3	24	33
Non-Ord	7	0	2	3	1	0	1	0	1	1	2	312	330
Total	19	10	15	7	5	14	4	3	4	5	5	524	615
%classified	42.1	40.0	53.3	28.6	0.0	71.4	0.0	100.0	0.0	0.0	60.0		

Table 13
Classification Matrix, Aggregated by Ordnance Size, with Threshold of 0.15

Classification	20mm	57-81mm	105-155mm	False Alarm
20mm	8	1	1	90
57-81mm	4	40	2	78
105-155mm	0	4	13	44
Non-Ordnance	7	6	5	312
Total	19	51	21	524
% classified	42.1	78.4	61.9	59.5

4. SUMMARY AND RECOMMENDATIONS

The GEM-3 data collected as part of the Advanced UXO Detection/ Discrimination Technology Demonstration at JPG have been analyzed to characterize the UXO classification capabilities of the GEM-3. Although the GEM-3 performed well in detecting anomalies at the site, the classification results achieved by Geophex at JPG were somewhat disappointing, especially for the larger ordnance types. Factors such as sensor coverage, sensor data variability, and the effect of size and depth of the UXO items used in the demonstration were investigated to identify possible problems or limitations of the GEM-3 sensor that might have contributed to the poor classification performance at JPG.

Sensor coverage of the target areas at a spacing of 0.5 m appears to be adequate. Several data points were acquired near each target. Tighter spacing of measurements would likely improve performance against very small targets like the 20-

mm projectiles. Good signatures for these targets were obtained only when the sensor was nearly centered on the target. A tighter search grid would produce more data to be analyzed but would increase the chances of having the sensor pass directly over the target. It is possible that the density of measurements near some targets was not sufficient to support the classification scheme used by Geophex.

The data points acquired near each target were individually compared with calibration data for the target's ordnance type so that the variability of the data could be examined. Even allowing for differences due to the differing orientation of the target relative to the sensor, the comparisons showed a high degree of variability among the data points near many targets. While at least one point near almost every target closely matched the signature of the correct ordnance type, there were other points near most targets that did not match the signature for any ordnance favorably. The degree of uncertainty in a given measurement makes classification unreliable, especially for small or deep targets. This report also presents statistical analysis of data of fixed targets over a period of time acquired by ERDC personnel with the GEM-3 in a preliminary attempt to determine the precision of the instrument.

The effect of the size and depth of the targets on classification was also examined. The smallest ordnance in the demonstration, 20-mm projectiles, were the only ordnance that were difficult to detect regardless of depth. All the other ordnance types produced strong responses in the sensor at shallower depths. However, the deepest targets of several ordnance types resulted in signal strength on the order of the sensor fluctuations, making reliable classification unlikely. To quantify the classification capabilities of the GEM-3, the targets were classified using a template-matching algorithm that compared the data point with the greatest total magnitude near each object to calibration signatures for the different ordnance types and assigned the object to the closest matching ordnance type. This procedure resulted in an exact classification match for nearly half of the targets for which calibration data were available and a match to a similarly sized target for more than two-thirds of the medium and large targets. This classification, based on a single selected data point for each detected object, is intended to serve as a baseline. In theory, more sophisticated algorithms that use all of the available data points near each object should perform better. However, because of the variability among data points near the same target, this may not be the case.

The results presented here indicate that the GEM-3 has outstanding potential to detect and classify UXO. While test parameters and limitations of the sensor and the positioning system contributed to some misclassifications of objects from the JPG demonstration, the primary problem identified in this analysis is the variability in sensor response throughout the demonstration. The data taken at JPG and ERDC-WES indicate that both drift and abrupt shifts in the level of sensor response occurred in the GEM-3 systems. A careful look into the extent and cause of these sensor variations is necessary to determine if they can be removed or characterized such that they may be minimized and not affect the results of the data analysis.

REFERENCES

1. J. Miller, T. Bell, D. Keiswetter, and D. Wright, "Feature-based characterization of UXO-like targets using broadband electromagnetic induction," *UXO Forum 2001 Proceedings*, UXO Forum 2001, New Orleans, Louisiana, 2001.
2. E. R. Cespedes, "Advanced UXO detection/discrimination technology demonstration - U.S. Army Jefferson Proving Ground, Madison, Indiana," Technical Report ERDC/EL TR-01-20, U. S. Army Engineer Research and Development Center, Vicksburg, Mississippi, 2001.
3. R. Welch and A. Homsey, "Datum shifts for UTM coordinates," *Photogrammetric Engineering & Remote Sensing* **63(4)**, 371-375, 1996.
4. I. J. Won, D. A. Keiswetter, D. R. Hanson, E. Novikova, and T. M. Hall, "GEM-3: A monostatic broadband electromagnetic induction sensor," *Journal of Environmental and Engineering Geophysics* **2(1)**, 53-64, 1997.
5. Geophex, Ltd. *GEM-3 Instruction Manual*," Geophex, Ltd., Raleigh, North Carolina, 1998.
6. I. J. Won, D. Keiswetter, and E. Novikova, "Electromagnetic induction spectroscopy," *Journal of Environmental and Engineering Geophysics* **3(1)**, 27-40, 1998.