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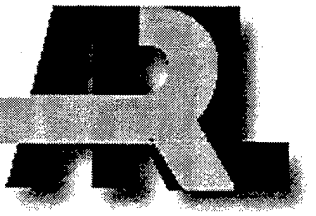

Gunner Tracking Models for the M1A1 Combat Vehicle Engineering Simulation

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Abstract

During fiscal years 1998 and 1999, an effort was conducted as part of a technology program annex with the U.S. Army Test and Evaluation Command to develop gunner tracking models for the U.S. Army Research Laboratory's Combat Vehicle Engineering Simulation (CVES). CVES contains engineering models of the fire control system, chassis-suspension, and the gunner for the M1A1 combat tank and the A3 version of the Bradley fighting vehicle system. This effort addresses the gunner model for the M1A1.

Gunner models were developed using the Xmath™ interactive system identification algorithms from the MATRIXx® software package along with measured gunner tracking error and estimated target rate data (gunner handle control output).

The resulting gunner tracking models are shown to be more accurate than the existing gunner tracking models used in CVES for two of the three maneuvering target paths that were considered in this study. Furthermore, the results demonstrate that usable models can be developed using the techniques discussed in this report.

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GUNNER TRACKING MODELS FOR THE M1A1 COMBAT VEHICLE ENGINEERING SIMULATION

1. INTRODUCTION

For fiscal years 1998 and 1999, the Weapons Analysis Branch (WAB), Ballistics and Weapons Concepts Division, Weapons and Materials Research Directorate (WMRD), of the U.S. Army Research Laboratory (ARL) continued by way of a technology program annex (TPA) with the U.S. Army Test and Evaluation Command (TECOM) to perform basic research and exploratory development in support of its virtual proving ground (VPG). When completed, the VPG will serve as a cohesive and comprehensive testing tool that leverages TECOM's current capabilities while adding modern modeling and simulation to provide better and faster test support at lower cost.

One of the major efforts undertaken for fiscal years 1998 and 1999 was to develop gunner tracking models for the WAB-developed Combat Vehicle Engineering Simulation (CVES). CVES contains detailed engineering models of the fire control system, chassis-suspension, and the gunner for both the Abrams M1A1 combat tank and the A3 version of the Bradley fighting vehicle system (BFVS-A3). Input to CVES are target path and the terrain over which the M1A1 and BFVS-A3 travel. CVES was built to determine the performance of the vehicles and their weapon systems.

The motivation for developing new gunner models for CVES was twofold. During the 1996 fiscal year, also as part of the TPA with TECOM, the output of the M1A1 portion of the CVES were compared to actual data. The results of this comparison showed that the simulation did a very good job of duplicating the lead angles but only a fair job of duplicating the tracking errors (Corcoran & Perkins 1997). Thus, there was a need to develop better gunner tracking models for CVES. Secondly, this effort demonstrated that usable models could be developed using measured data. This will enhance ARL's ability to develop human driver models that will be required for the future Ground Vehicle Mobility Model.

It was unnecessary to conduct a test to collect the data to develop the gunner tracking models since data from a test conducted by the Aberdeen Test Center (ATC) in the 1992-93 time frame were already available. The purpose of this previous test had been to determine the feasibility of incorporating an autotracker into the M1A1. Manual tracking as well as autotracking was considered in the test, but only the data from the manual tracking trials were considered in the

gunner model development. Data from this same test had been used in the 1996 comparison of the M1A1 CVES results with actual data.

The gunner's input is tracking error and the gunner's output is handle control position. The gunner moves the handle control in such a way as to keep the sight reticle on the target, thereby minimizing the tracking error. In the M1A1, the output of the handle control is a signal that is an estimate of the target's angular rate. Since the handle control position was not measured directly during the test, the output signal from the handle control, which was measured, was used as a measure of the gunner's output. This is a reasonable substitute for the handle control position since its output is from a transducer that converts handle control position to a voltage proportional to estimated target rate. Thus, the signals of interest from the test for this study were gunner tracking error and the estimated target rate.

Gunner tracking models were developed using the Xmath™ interactive system identification algorithms from the MATRIXx® software package along with the measured gunner tracking error and estimated target rate data. These models were compared to the existing CVES gunner models to determine if they were more accurate.

The purpose of this report is to describe the development of the gunner tracking models for the M1A1. Similar models will be developed for the BFVS-A3 when the required test data are available.

2. PROCEDURES

As mentioned, the measured input and output gunner data were obtained from a test conducted in the 1992-93 time frame to determine the feasibility of installing an autotracker in the M1A1. This testing was conducted in ATC's moving target simulator (MTS). The MTS is an air-supported hemispherical structure that is 60 meters in diameter. The system undergoing test is positioned inside the MTS and instrumented appropriately. A laser spot projected onto the wall of the MTS represents the target. Target motion at a given range is simulated by driving the laser spot with a computer-generated signal that is proportional to the target's angular displacement referenced to the system being tested. The gunner tracks the spot as though it were a target; the simulated range to the target is manually input by the gunner to the ballistic computer (since the laser range finder cannot be used to measure range in the test setup), and the tank's fire control system aims the gun. Time histories of various engineering quantities are recorded at numerous test points for each trial. A big advantage of conducting tests in the MTS is the repeatability of target motion.

Testing was conducted against two evasive targets: the ground vehicle antitank missile test (ATMT) target and the aerial Ballistics Research Laboratory (BRL) target. The BRL target represents an evasively maneuvering helicopter that delivers antitank guided missiles (ATGMs), and the ATMT target represents an evasive tank maneuvering randomly. The ATMT target was chosen because a portion of the materiel need effectiveness specifications for the M1 and the M1A1 is based on this target. An evasive helicopter target was chosen because such a target is specified in the required operational capability document for the M830A1 round for the M1A1. The ATMT target represents the actual motion of a tactical vehicle measured during field tests, while the BRL target is an analytical target.

The lateral motion of the ATMT and BRL targets is shown in Figures 1 and 2, respectively. A power spectral density (PSD) analysis of the ATMT lateral path showed that most of the target motion occurs at frequencies below 0.31 rad/s (0.05 Hz). The BRL lateral path motion is occurring at an average velocity of 10 m/s with the target accelerating and decelerating about this point in a sine wave fashion at a frequency of 0.31 rad/s.

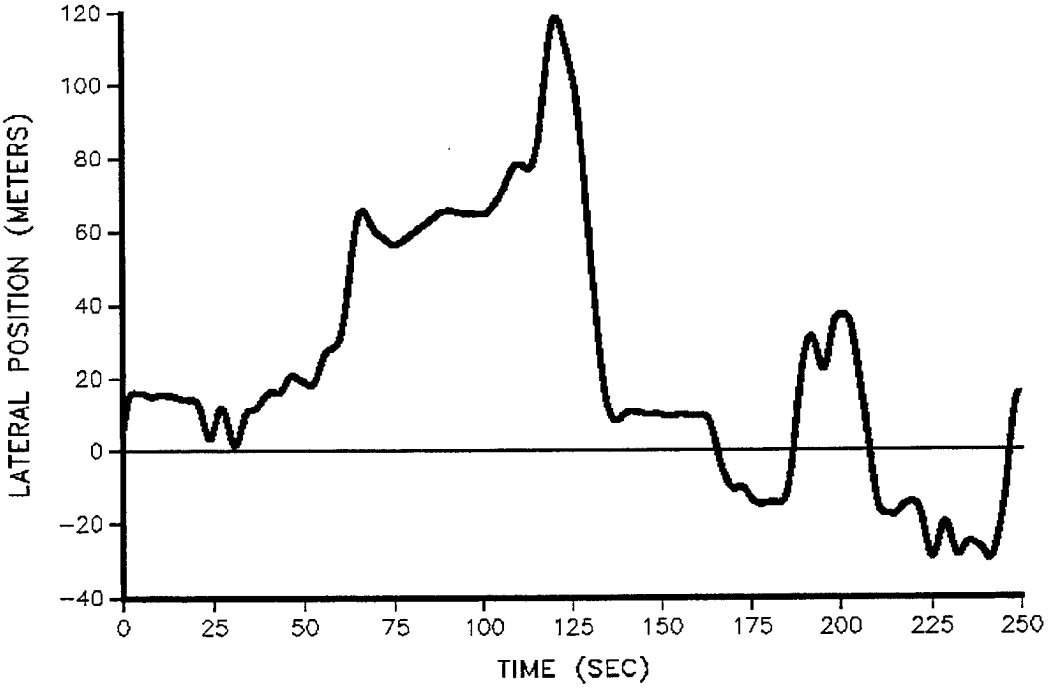

Figure 1. ATMT Target—Lateral Motion.

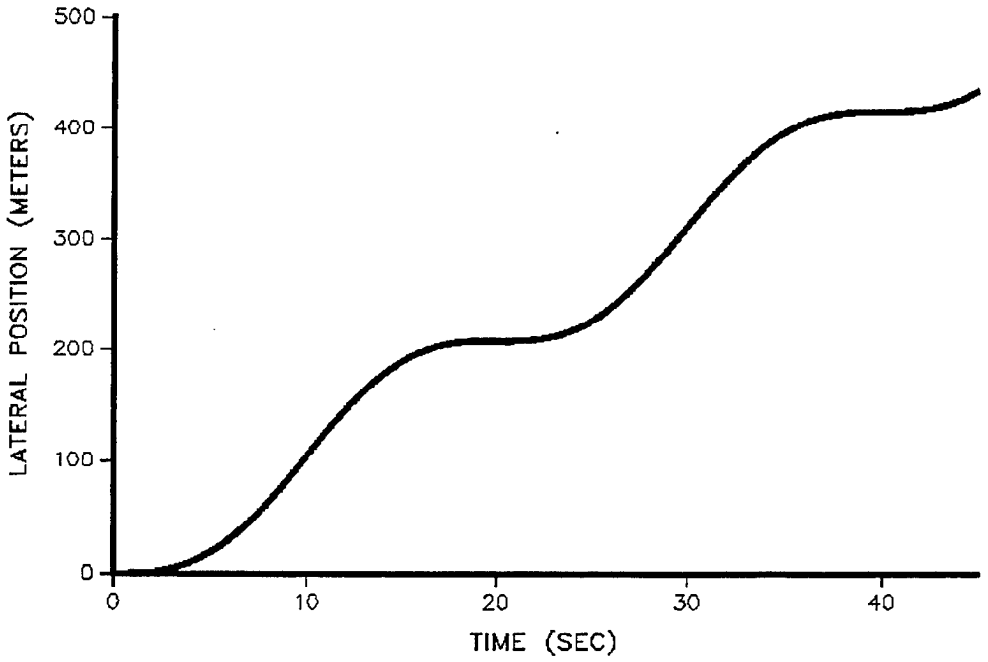

Figure 2. BRL Target—Lateral Motion.

The BRL target also has a vertical motion component (shown in Figure 3). The ATMT target does not have a vertical component since it describes a ground target. These two targets yielded the three target paths that were considered in this study.

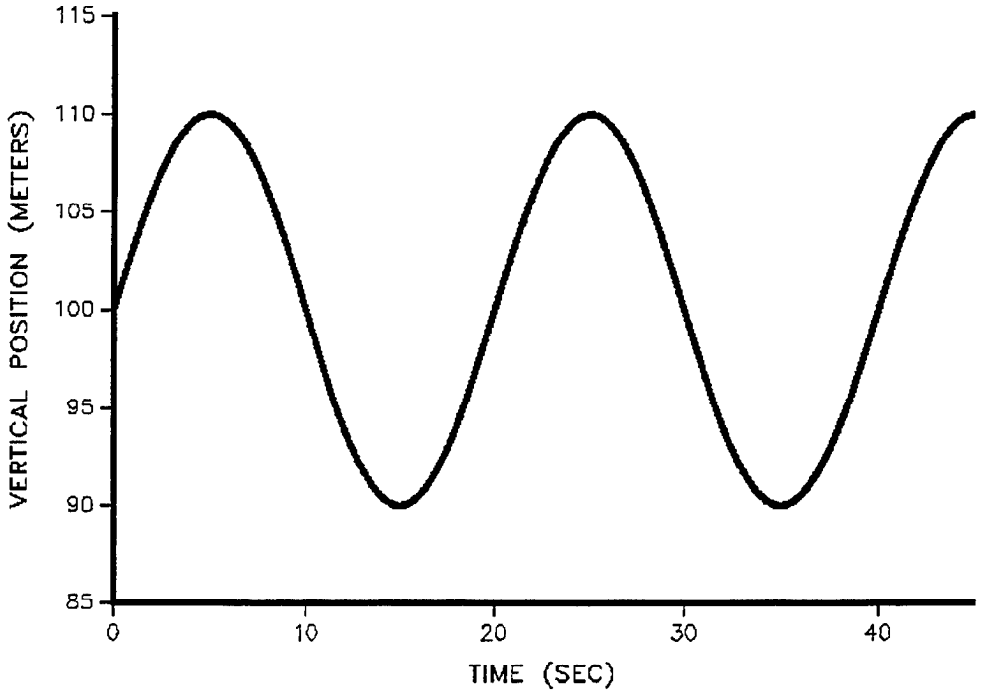

Figure 3. BRL Target—Vertical Motion.

These targets were maneuvering at simulated ranges of 1, 2, 3, and 4 kilometers. When engaging the ATMT target, the gunners simulated firing kinetic energy (KE) rounds as far as 4 kilometers and high explosive antitank (HEAT) rounds as far as 3 kilometers. When engaging the BRL target, the gunners simulated firing KE and training (TRNG) rounds as far as 4 kilometers. The training round served as a surrogate for the M830A1 round since the flight times of these two rounds are similar.

Typically, 15 to 20 manual tracking trials were conducted for each test condition. To obtain representative gunner input and output for each of the conditions tested, tracking errors from similar trials were averaged together as a function of time, as were the estimated target rate signals. These average time histories were then used as the input to the MATRIXx® Xmath™ interactive system identification algorithms, and a gunner tracking model was developed for each of the test conditions. Since the ATMT path had no vertical motion, the elevation tracking errors and handle control output signals for this case were mostly noise. Therefore, no models were developed for the gunner tracking the ATMT path in elevation. Typical averaged time histories of the gunner input and output when tracking each of the target paths are shown in Figures 4 through 6, respectively.

The first step in the model development process was to remove the mean from the tracking error and estimated target rate signals. The resulting time histories were then split so that the first half of the time history data was used to identify the model and the second half was used for model validation. The next step was to select an identification algorithm. There are a number of MATRIXx® algorithms to choose from, but only two of them produced stable models for just about all the test conditions considered. These two algorithms are called least squares (LS) and subspace identification (SDS). As the name implies, the least squares algorithm uses least squares techniques to identify models, whereas the subspace identification algorithm uses Kalman filter techniques to identify models. For details about these identification algorithms, the reader is referred to the MATRIXx® manuals (Integrated Systems, 1996).

The output of each of these identification algorithms is a series of single input, single output linear time-invariant models. The output of the LS algorithm produced models of order one through ten, and the SDS algorithm produced models of order one through three. Thus, for each test condition, 13 gunner models were identified, making a total of 299 models (3 target paths x [3 or 4] ranges x 2 rounds x 13 models per test condition)—obviously an unrealistic number of models to use in CVES.

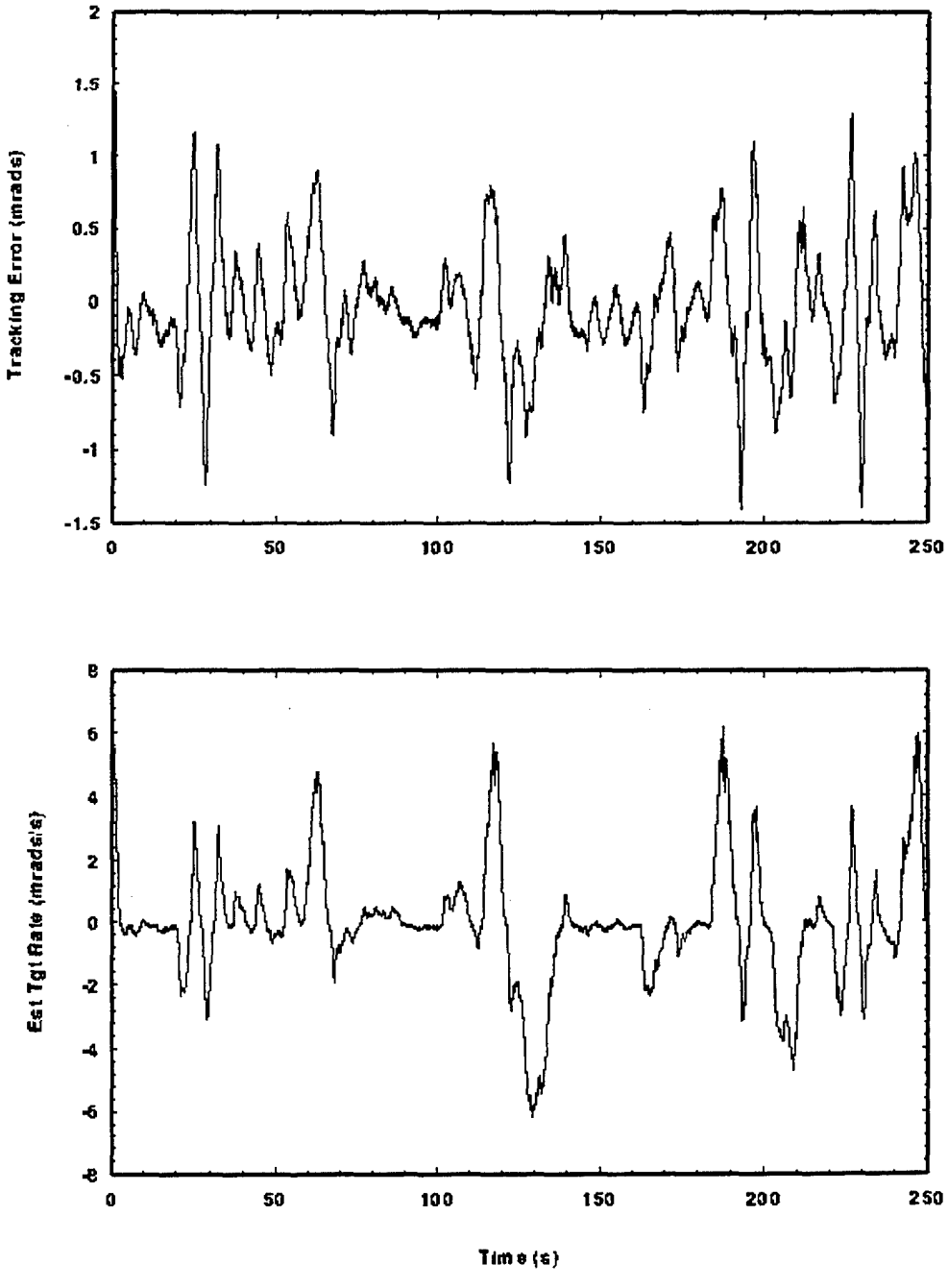

Figure 4. Gunner Input and Output—ATMT Lateral Target Path (target range = 2.0 km, KE round).

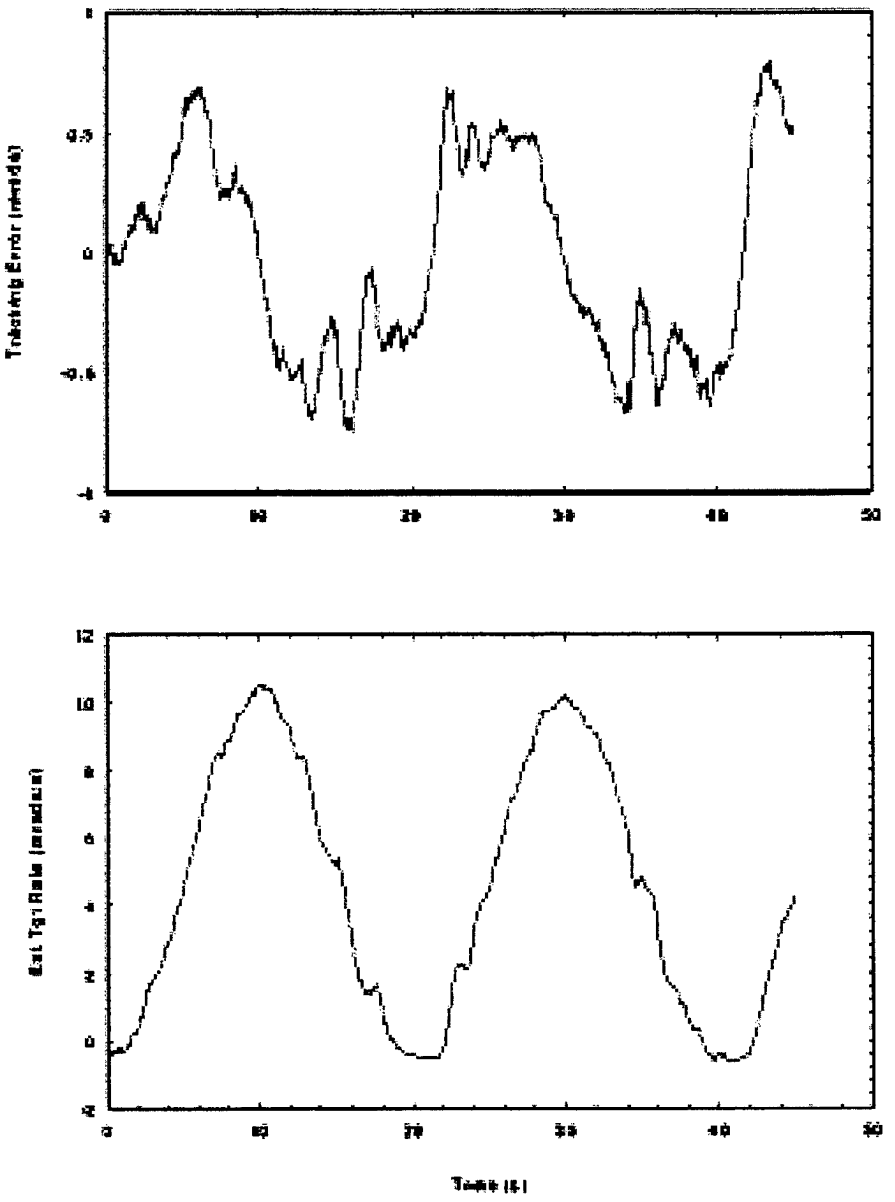

Figure 5. Gunner Input and Output—BRL Lateral Target Path (target range = 2.0 km, TRNG round).

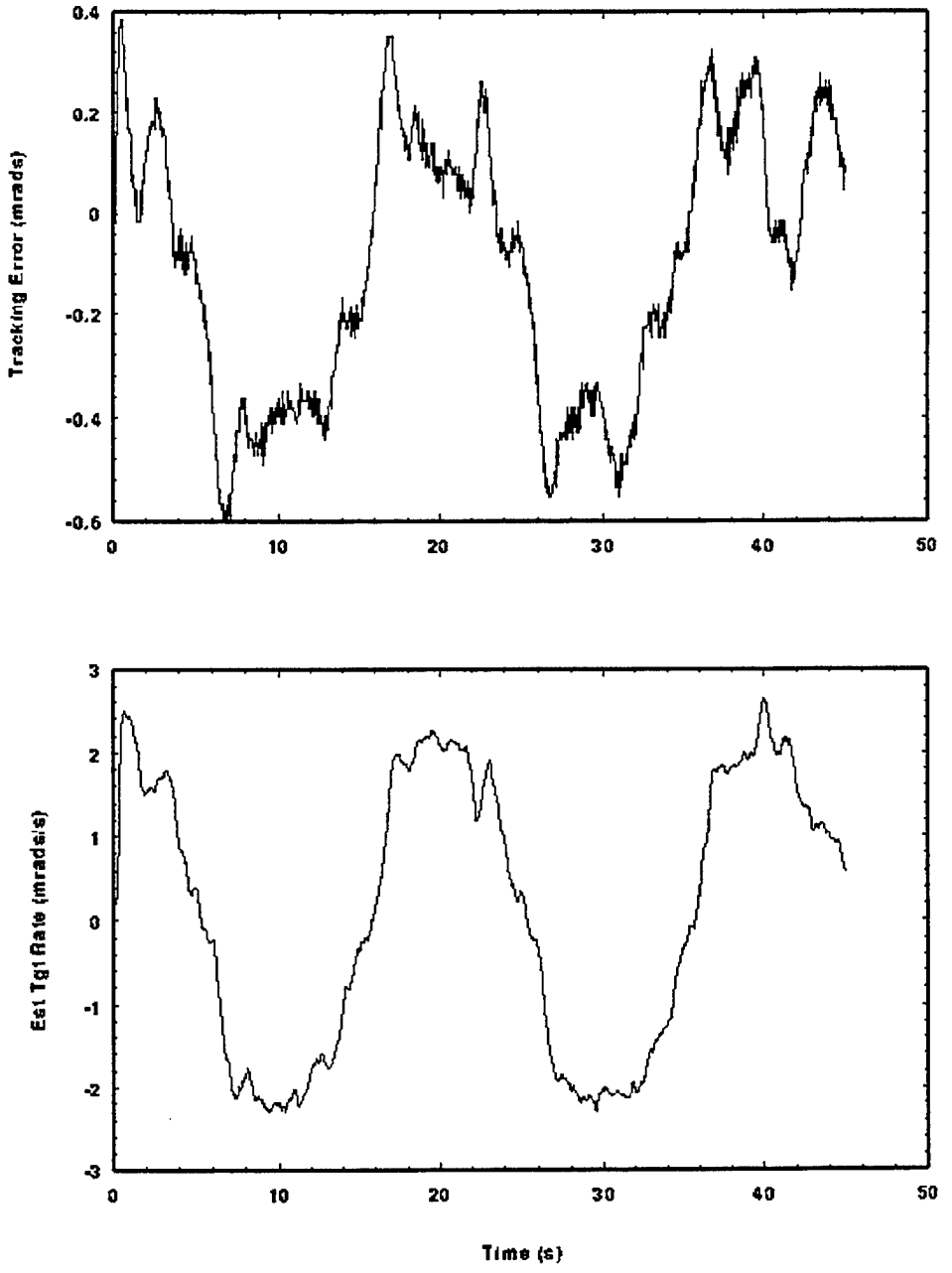

Figure 6. Gunner Input and Output—BRL Vertical Target Path (target range = 2.0 km, TRNG round).

Ideally, it would be advantageous from a CVES ease-of-modeling-and-use standpoint to have one gunner model for all test conditions. However, it was obvious from the beginning of this study that three fundamental gunner models were being identified—one for each target path

tracked. Thus, it was decided that one gunner model would be installed in CVES for each target path tracked, provided that these new models were more accurate than the existing CVES gunner models. The problem then became how to select the appropriate gunner models from all the models identified.

To solve this problem, the accuracy of each identified model was computed by employing the so-called error norm. The error norm provides a measure of how well the model output agrees with the actual measured output. It is defined in the MATRIXx® literature as the standard deviation of the model error divided by the standard deviation of the actual measured gunner output. The model error is the difference between the model output and the actual gunner output. Therefore, a model with a lower error norm would be a more accurate model. For each target path, the error norms for those models identified using the same identification algorithm and of the same order were averaged together. The model order was then selected for each combination of target path and identification algorithm by considering the average error norms or accuracies.

A review of the average error norms for each identification algorithm and for each target path showed that the LS first order models were nearly as accurate or more accurate than the higher order LS models and the SDS first order models were always more accurate than the higher order SDS models. This indicated that a first order model rather than a higher order model could be used to represent the gunner. The question then became which first order model (the LS or SDS model) to use. For each of the BRL target paths, the first order models identified by the LS and SDS algorithms had almost the same average accuracy. However, for the ATMT lateral path, the first order models identified by the SDS algorithm were slightly more accurate than the first order models identified by the LS algorithm. Therefore, it was decided that the first order gunner models identified by the SDS algorithms would serve as the fundamental gunner models for the M1A1 CVES.

The coefficients of the SDS first order models now had to be determined. In the frequency domain, this meant that the lag frequency, lead frequency, and the gain of each model or transfer function had to be determined. The averaging process was again used to determine these coefficients for the three fundamental transfer functions. For a given target path, the average of the SDS first order model lag frequencies was computed, as was the average of the lead frequencies. These average frequencies became the lag and lead frequencies of the first order SDS model associated with a given target path.

In addition to determining the lag and lead frequencies of the transfer function, it was also necessary to determine the steady state gain of the transfer function. The steady state gain of the transfer function is the ratio between the estimated target rate and the tracking error at zero frequency. As it occurred, this gain tended to decrease as the range to the target increased. For a given target path, the gains of the first order SDS models at a given range were averaged, and a second order polynomial was fitted to these averaged gains to estimate the steady state gain of the gunner model as a function of range.

The form of the resulting gunner model when each target path was tracked was therefore a first order model with a gain that varied as a function of range to the target.

The accuracy of these newly developed gunner models was compared to the accuracy of the existing gunner models that are used in CVES. There would be no reason to use the new models in CVES unless they were more accurate than the existing models. The present CVES has one gunner model for the azimuth axis and one gunner model for the elevation axis, and these same models are used regardless of the M1A1-target scenario. The accuracies of the CVES models were computed just as the accuracies of the newly developed SDS first order models were. The models with the smaller error norms were considered to be the more accurate models.

3. RESULTS

3.1. Gunner Model Selection

The error norms or accuracies for each of the gunner models that were identified using the LS algorithm and the SDS algorithm when the ATMT lateral target path was tracked, are shown in Tables 1 and 2, respectively.

From Table 1, it is seen that on the average, the error norms for those gunner models that were identified from the ATMT lateral target path tracking data and using the LS algorithm are decreasing as the model order is increasing from the first through tenth order. This means that the output from the higher order models is showing somewhat better agreement with measured data. On the other hand, it is seen from Table 2 that the error norms for those models that were identified using the SDS algorithm are increasing as the model order is increasing from the first through third order. This implies that the output from the higher order SDS models is showing poorer agreement with measured data. However, it is seen from the average error norms that the first order SDS model is almost as accurate as the higher order LS models.

Table 1. Error Norms for Models Identified Using the Least Squares Algorithm—ATMT Lateral Target Path

RANGE (km)	ROUND	LEAST SQUARES MODEL ORDER									
		1	2	3	4	5	6	7	8	9	10
1.0	KE	50	45	44	43	42	41	42	41	41	43
2.0	KE	51	50	49	48	47	46	45	44	43	42
3.0	KE	59	56	55	55	54	54	53	50	50	49
4.0	KE	48	46	46	46	45	44	44	42	41	40
1.0	HEAT	38	33	29	28	27	26	26	26	26	26
2.0	HEAT	45	40	39	36	33	32	30	30	29	28
3.0	HEAT	37	33	33	32	32	32	31	31	31	32
AVERAGES		47	43	42	41	40	39	39	38	37	37

(Table entries are in percent.)

Table 2. Error Norms for Models Identified Using the Subspace Identification Algorithm—ATMT Lateral Target Path

RANGE (km)	ROUND	SUBSPACE IDENTIFICATION MODEL ORDER		
		1	2	3
1.0	KE	47	64	64
2.0	KE	48	57	57
3.0	KE	55	64	65
4.0	KE	46	57	75
1.0	HEAT	31	41	42
2.0	HEAT	37	50	55
3.0	HEAT	30	36	38
AVERAGES		42	53	57

(Table entries are in percent.)

The error norms or accuracies for each of the gunner models that were identified using the LS algorithm and the SDS algorithm when the BRL lateral target path was tracked, are shown in Tables 3 and 4, respectively.

In Table 3, it is seen that on the average, the error norms for those gunner models that were identified from the BRL lateral target path tracking data and using the LS algorithm are about the

same for all model orders. This means that the output from the lower order LS models is just about as accurate as the output from the higher order LS models. The sixth through tenth order LS models identified for the 3.0-km case when the KE round was "fired" were the only ones in this entire study that were found to be unstable.

Table 3. Error Norms for Models Identified Using the Least Squares Algorithm—BRL Lateral Target Path

RANGE (km)	ROUND	LEAST SQUARES MODEL ORDER									
		1	2	3	4	5	6	7	8	9	10
1.0	KE	34	29	33	29	29	28	31	36	37	32
2.0	KE	17	18	18	20	19	30	28	39	33	28
3.0	KE	19	23	21	21	21	31	39	68	51	37
4.0	KE	19	25	20	20	20	26	23	23	25	21
1.0	TRNG	20	29	20	22	17	19	20	15	15	17
2.0	TRNG	19	18	18	18	19	19	19	19	19	20
3.0	TRNG	42	20	29	24	23	16	18	19	21	21
4.0	TRNG	30	25	28	29	29	28	27	26	27	26
AVERAGES		25	23	23	23	22	25	26	31	29	25

(Table entries are in percent.)

Table 4. Error Norms for Models Identified Using the Subspace Identification Algorithm—BRL Lateral Target Path

RANGE (km)	ROUND	SUBSPACE IDENTIFICATION MODEL ORDER		
		1	2	3
1.0	KE	31	25	27
2.0	KE	17	33	46
3.0	KE	26	46	41
4.0	KE	28	30	35
1.0	TRNG	20	29	65
2.0	TRNG	19	20	22
3.0	TRNG	41	21	28
4.0	TRNG	31	33	31
AVERAGES		27	30	37

(Table entries are in percent.)

From Table 4, it is seen that the error norms for those models that were identified using the SDS algorithm are increasing as the model order is increasing from the first through third order. Once more, the output from the higher order SDS models is showing poorer agreement with measured data. It is also seen from the average error norms that the first order SDS model is just about as accurate as all the LS models.

The error norms for each of the gunner models that were identified using the LS algorithm and the SDS algorithm when the BRL vertical target path was tracked, are shown in Tables 5 and 6, respectively.

Table 5. Error Norms for Models Identified Using the Least Squares Algorithm—BRL Vertical Target Path

RANGE		LEAST SQUARES MODEL ORDER									
(km)	ROUND	1	2	3	4	5	6	7	8	9	10
1.0	KE	34	40	38	38	38	37	35	35	34	33
2.0	KE	29	28	29	29	31	32	30	31	30	30
3.0	KE	23	24	24	27	26	25	26	25	26	26
4.0	KE	14	14	14	14	15	16	15	16	17	16
1.0	TRNG	33	35	35	35	38	37	34	34	34	33
2.0	TRNG	27	28	27	27	27	27	27	28	28	28
3.0	TRNG	24	22	22	22	23	23	24	24	26	23
4.0	TRNG	28	28	29	30	31	31	32	33	33	33
AVERAGES		27	27	27	28	29	29	28	28	29	28

(Table entries are in percent.)

In Tables 5 and 6, the same trends are seen in the average error norms that were seen previously. For those models identified using the BRL vertical target path tracking data and the LS algorithm, the error norms are about the same for all model orders, and for those models identified using the SDS algorithm, the error norms are increasing as the model order is increasing. Also, it is again seen from the average error norms that the first order SDS model is as accurate as all the LS-developed models.

The results in these tables show that the first order models are nearly as accurate or more accurate than the higher order models. For the two BRL paths, the LS and SDS first order models exhibit nearly the same accuracy. However, for the ATMT lateral path, the first order

SDS models are slightly more accurate than the first order LS models. Therefore, a first order SDS model was selected to be representative of a gunner tracking a maneuvering target.

Table 6. Error Norms for Models Identified Using the Subspace Identification Algorithm—BRL Vertical Target Path

RANGE (km)	ROUND	SUBSPACE IDENTIFICATION MODEL ORDER		
		1	2	3
1.0	KE	34	34	37
2.0	KE	27	30	36
3.0	KE	22	25	22
4.0	KE	14	25	30
1.0	TRNG	33	34	36
2.0	TRNG	30	33	32
3.0	TRNG	23	23	25
4.0	TRNG	26	33	31
AVERAGES		26	30	31

(Table entries are in percent.)

The model is simple in that it has only one lag and one lead frequency. The form of the model, or transfer function *G(s)* as a function of frequency, is shown in the following equation:

$$G(s) = K\frac{(\tau_{lead}s + 1)}{(\tau_{lag}s + 1)}$$

In this equation, s is the LaPlace transform operator, K is the steady state gain, τ_{lead} is the lead time constant, and τ_{lag} is the lag time constant. The reciprocals of the lead and lag time constants, ω_{lead} and ω_{lag}, are the lead and lag frequencies expressed in rad/s.

3.2. Lag and Lead Frequencies and Gain Selection

Tables 7 through 9 show the lag and lead frequencies along with the gains for each individual SDS first order model that was identified for each test condition.

In Table 7, it is seen from the standard deviations that the lag and lead frequencies are rather consistent for the models developed using the ATMT lateral target path tracking error and estimated target rate data. It is also seen that the average lead frequency is larger than the average

lag frequency. A PSD analysis of the tracking error shown in Figure 4 indicated that most of the tracking error occurs at frequencies below 1.25 rad/s. The lead term will not have much of an effect on the input amplitude, but it will affect the phase shift between the input and output, especially for those input frequencies that are greater than 0.30 rad/s. It is also seen in Table 7 that the steady state gains are decreasing as the target range is increasing.

Table 7. Gunner Model Parameters—ATMT Lateral Target Path

RANGE (km)	ROUND	SDS MODEL PARAMETERS		
		ω_{lag}	ω_{lead}	K
1.0	KE	0.60	2.87	7.22
2.0	KE	0.49	3.40	6.00
3.0	KE	0.41	3.80	5.46
4.0	KE	0.54	4.17	3.50
1.0	HEAT	0.39	2.53	9.05
2.0	HEAT	0.37	2.17	5.80
3.0	HEAT	0.34	1.68	3.69
AVERAGES		0.45	2.95	NA
STANDARD DEVIATION		0.10	0.90	NA

Table 8. Gunner Model Parameters—BRL Lateral Target Path

RANGE (km)	ROUND	MODEL PARAMETERS		
		ω_{lag}	ω_{lead}	K
1.0	KE	0.073	-25.19	62.07
2.0	KE	0.058	27.10	60.32
3.0	KE	0.032	7.17	81.82
4.0	KE	0.054	3.09	38.99
1.0	TRNG	0.070	16.36	50.56
2.0	TRNG	0.037	9.22	82.91
3.0	TRNG	0.052	4.73	47.90
4.0	TRNG	0.113	3.18	12.63
AVERAGES		0.061	10.12	NA
STANDARD DEVIATION		0.025	8.79	NA

Table 9. Gunner Model Parameters—BRL Vertical Target Path

RANGE (km)	ROUND	MODEL PARAMETERS		
		ω_{lag}	ω_{lead}	K
1.0	**KE**	0.48	3.77	15.87
2.0	**KE**	0.69	11.21	9.32
3.0	**KE**	0.77	12.32	8.19
4.0	**KE**	0.92	687.96	5.28
1.0	**TRNG**	0.45	3.48	11.83
2.0	**TRNG**	1.12	13.22	7.17
3.0	**TRNG**	0.93	11.28	4.38
4.0	**TRNG**	0.77	2.18	2.95
AVERAGES		0.77	8.21	NA
STANDARD DEVIATION		0.23	4.81	NA

Referring to Table 8, it is seen that the lag frequencies are again rather consistent, but the lead frequencies are more variable. Furthermore, the lead frequency is negative when the 1.0-km BRL lateral target path is tracked and the KE round is "fired." A system or model with this characteristic is referred to as a "non-minimum phase system." The gain of a non-minimum phase system will not differ from that of a minimum phase system, but the phase shift between the system's input and output will differ. Therefore, this lead frequency was considered as an outlier and was not considered in the statistics.

A PSD analysis of the tracking error shown in Figure 5 indicated that the tracking error occurs predominantly at a frequency of 0.31 rad/s, but there are higher frequencies, as great as about 1.50 rad/s, present in the signal. The average lead frequency is much higher than 1.50 rad/s and therefore will not have much of an effect on either the input amplitude or phase shift between the input and output.

The trend of the steady state gains for these models is not as clearly defined as it was for the previous models.

In Table 9, the lag frequencies are again rather consistent and the lead frequencies are more variable. The lead frequency for the model identified with tracking the BRL vertical target path at

4 kilometers and "firing" the KE round is shown to have a lead frequency of 687.96 rad/s (obviously an outlier) and was not considered in the statistics.

Like the other models, the lead frequency for this model is considerably higher than the lag frequency. A PSD analysis of the tracking error shown in Figure 6 also indicated that the tracking error occurs predominantly at a frequency of 0.31 rad/s, with higher frequencies as great as about 1.50 rad/s present in the signal. The lead term will have no effect on the input amplitude but it will have an effect on the phase shift between the input and output, especially when the input signal frequency is greater than 0.82 rad/s.

The steady state gains associated with the models identified when the BRL vertical target path is tracked are seen to be decreasing as the range to the target is increasing.

Having determined the average lag and lead frequencies for the first order SDS models associated with each of the target paths, we now determined the gain function for each model. It is seen in Tables 7 and 9, and to some degree in Figure 8, that the gunner's gain tends to decrease as the range to the target increases. Therefore, a second order polynomial fit was applied to the averages of the identified gains. The equations for the gain of each model and the root sum square (RSS) of the differences between the average gain and the polynomial fit are shown in Table 10.

Table 10. Gunner Model Gain Functions

MODEL	GAIN FUNCTION	RSS
ATMT LATERAL	$K = 0.29R^2 - 2.97R + 10.79$	0.15
BRL LATERAL	$K = -13.59R^2 + 58.11R + 11.28$	2.29
BRL VERTICAL	$K = 0.86R^2 - 7.41R + 20.21$	0.86

Consistent with the identified gains, it is seen from Table 10 that the fitted gains associated with each of the target paths are different. Furthermore, referring to the RSS of the errors for each of the models, the gain functions all show good agreement with the identified gains. These gain functions are only good for target ranges of 1 to 4 kilometers.

The results presented in this section show that the gunner's transfer function depends on the target path that is tracked since the average lag and lead frequencies and the gain function differ for each path tracked.

3.3. Comparison of Gunner Tracking Models

The error norms or accuracies for the newly developed average SDS and existing CVES azimuth gunner models when the ATMT lateral target path is tracked are shown in Table 11.

Table 11. Error Norms of the SDS and CVES Models—ATMT Lateral Target Path

RANGE (km)	ROUND	MODEL	
		SDS	CVES-AZ
1.0	KE	42	248
2.0	KE	46	229
3.0	KE	57	156
4.0	KE	43	248
1.0	HT	39	356
2.0	HT	44	308
3.0	HT	52	503
AVERAGES		46	293

(Table entries are in percent.)

In Table 11, it is seen that individually and on the average, the SDS model error norms are considerably smaller than the CVES azimuth model error norms. This indicates that the SDS gunner tracking model is considerably more accurate than the CVES azimuth gunner tracking model when the ATMT lateral target path is tracked.

The error norms for the SDS and CVES azimuth gunner models when the BRL lateral target path is tracked are shown in Table 12. These results indicate that the SDS gunner model is not as accurate as the CVES azimuth gunner model when the BRL lateral path target is tracked. In most of the cases, and on the average, the SDS model error norms are larger than the CVES azimuth model error norms.

The error norms for the SDS and CVES models when the BRL vertical target path is tracked are shown in Table 13.

Table 12. Error Norms of the SDS and CVES Models—BRL Lateral Target Path

RANGE (km)	ROUND	MODEL	
		SDS	CVES-AZ
1.0	KE	38	38
2.0	KE	72	45
3.0	KE	85	56
4.0	KE	47	49
1.0	TRNG	39	31
2.0	TRNG	77	39
3.0	TRNG	94	46
4.0	TRNG	64	43
AVERAGES		65	43

(Table entries are in percent.)

Table 13. Error Norms of the SDS and CVES Models—BRL Vertical Target Path

RANGE (km)	ROUND	MODEL	
		SDS	CVES-EL
1.0	KE	47	66
2.0	KE	38	62
3.0	KE	38	67
4.0	KE	29	64
1.0	TRNG	55	58
2.0	TRNG	32	48
3.0	TRNG	38	42
4.0	TRNG	49	39
AVERAGES		41	56

(Table entries are in percent.)

The error norm results presented in Table 13 show that the SDS model is more accurate than the CVES elevation model for all but one of the test conditions, and on the average, when the BRL vertical target path is tracked.

In summary, the first order SDS gunner models are more accurate than the present CVES models when the ATMT lateral target path and BRL vertical target path are tracked. The first order SDS model is not as accurate as the CVES azimuth model when the BRL lateral target path is tracked.

4. DISCUSSION

The results presented in Section 3 show that first order SDS models are adequate to describe the gunner when each of the target paths considered in this study is tracked. However, the coefficients of the first order models differ, depending on the target path tracked. The fact that the model coefficients differ implies that the gunners are adapting their transfer function to the target path being tracked. The differences in the SDS azimuth models can readily be seen in Figure 7, which shows typical frequency responses (gain and phase responses) of the azimuth models developed from gunner input and output data when the ATMT and BRL lateral target paths are tracked. Also shown in Figure 7 is the frequency response of the existing CVES azimuth model. These frequency responses are representative of the gunner tracking a target at 2.0 km.

Over the tracking error frequency range of interest for the ATMT path (0 to 1.25 rad/s), the ATMT azimuth SDS model has a lower gain and less phase shift between the output and input than the BRL azimuth model. The difference in the phase responses between the ATMT and BRL azimuth models is consistent with the time histories of the gunner input and output for these two paths shown in Figures 4 and 5. In Figure 4, it is seen that there is little phase shift between the tracking error and the estimated target rate when the ATMT lateral target path is tracked. From Figure 7, it is seen that the model's phase shift is less than 50° over the frequency range of interest for the ATMT lateral target path.

The BRL lateral target path tracking errors are occurring predominantly at a frequency of 0.31 rad/s. In Figure 5, it appears that there is about 90° of phase shift between the tracking error and estimated target rate at this frequency. From Figure 7, it is seen that the model's phase shift is about 80° at a frequency of 0.31 rad/s.

The gain of the ATMT azimuth SDS model is also consistent with the gunner input and output shown in Figure 4. From Figure 4, it is seen that the gain at the lower frequencies when the ATMT lateral target path is tracked is about 6 or 16 dB. From Figure 7, it is seen that the ATMT azimuth SDS model gain is also about 16 dB at the lower frequencies.

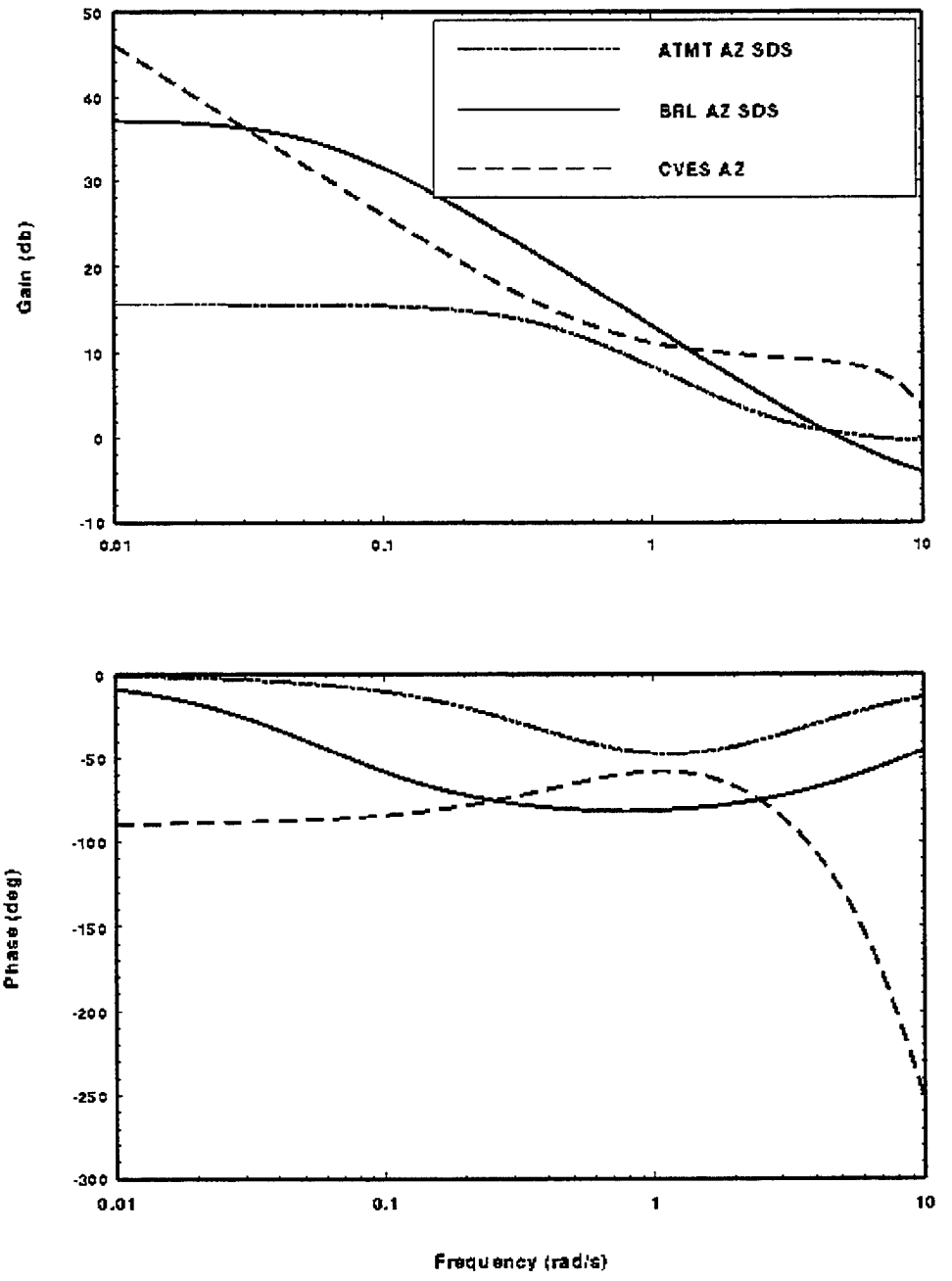

Figure 7. Frequency Responses of the Azimuth Gunner Models (target range = 2.0 km).

The gain of the BRL azimuth SDS model is not as consistent with the gunner input and output as is the ATMT azimuth SDS model. From Figure 5, the gain between the input and

output is on the order of 11 or 21 dB. In Figure 7, the gain of the BRL azimuth SDS model at a frequency of 0.31 rad/s is about 25 dB.

The frequency response of the model developed for the gunner when the BRL vertical target path is tracked is shown in Figure 8. Also shown in Figure 8 is the frequency response of the existing CVES elevation model. Both the gain and the phase of the BRL elevation SDS model are consistent with the time histories of the gunner input and output shown in Figure 6. From Figure 6, the gain at 0.31 rad/s is estimated to be about 7 or 17 dB, and there is little, if any, phase shift. From Figure 8, it is seen that the gain of the BRL elevation SDS model is about 18 dB and the phase shift is about 20° at a frequency of 0.31 rad/s.

The results also show that the SDS gunner models are more accurate than the existing CVES gunner models when the ATMT lateral target path and BRL vertical target path are tracked but not as accurate when the BRL lateral target path is tracked. A comparison of the ATMT and CVES azimuth model output with actual measured data is shown in Figure 9. It is readily seen that the output of the ATMT azimuth SDS model is in much closer agreement with the measured output.

A similar comparison is shown in Figure 10 for the BRL azimuth models. It is seen that the CVES azimuth model output agrees better with the measured data than the output of the BRL azimuth SDS model does. The BRL azimuth SDS model output agrees in phase with the measured data, but the model over-predicts the amplitude. This is consistent with the frequency response plots shown in Figure 7, whereby the gain of the BRL SDS model is greater than the gain of the CVES model. Except for the gain difference, the frequency responses of the BRL azimuth SDS model and the CVES azimuth models are similar in the vicinity of the path frequency. Over the frequency range of 0.1 to 1.0 rad/s, the gain of both models is decreasing at a rate of about 20 dB/decade, and at the BRL path frequency of 0.31 rad/s, the phase shift of both models is about the same. If the gain of the BRL azimuth SDS model were reduced by about 6 dB, the output of the two models would be close to being the same.

The comparison between the output of the BRL elevation SDS and CVES elevation models is shown in Figure 11. In elevation, the output of the BRL elevation SDS model is in better agreement with the actual data. Both models correctly predict the phase of the output, but the CVES elevation model under-predicts the output amplitude. This again is consistent with the frequency responses shown in Figure 8. The BRL elevation SDS model has about a 6-dB larger gain than the CVES elevation model at a frequency of 0.31 rad/s. It is also seen in Figure 8 (and Table 9) that the bandwidth (frequency at which the gain is 3 dB less than the steady state gain)

of the BRL elevation SDS model is 0.77 rad/s (ω_{lag}) whereas the bandwidth of the CVES elevation model is 10 rad/s.

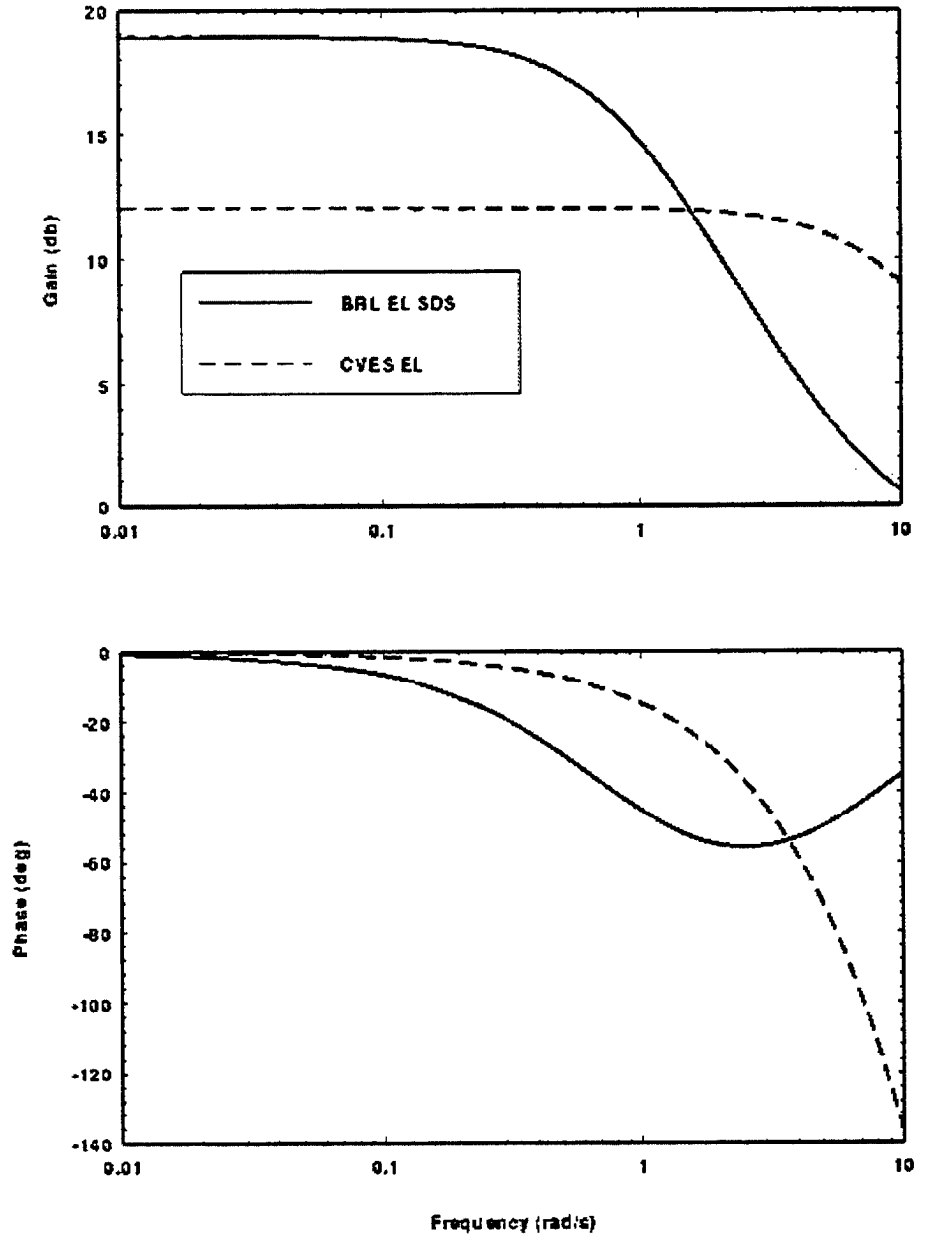

Figure 8. Frequency Responses of the Elevation Gunner Models (target range = 2.0 km).

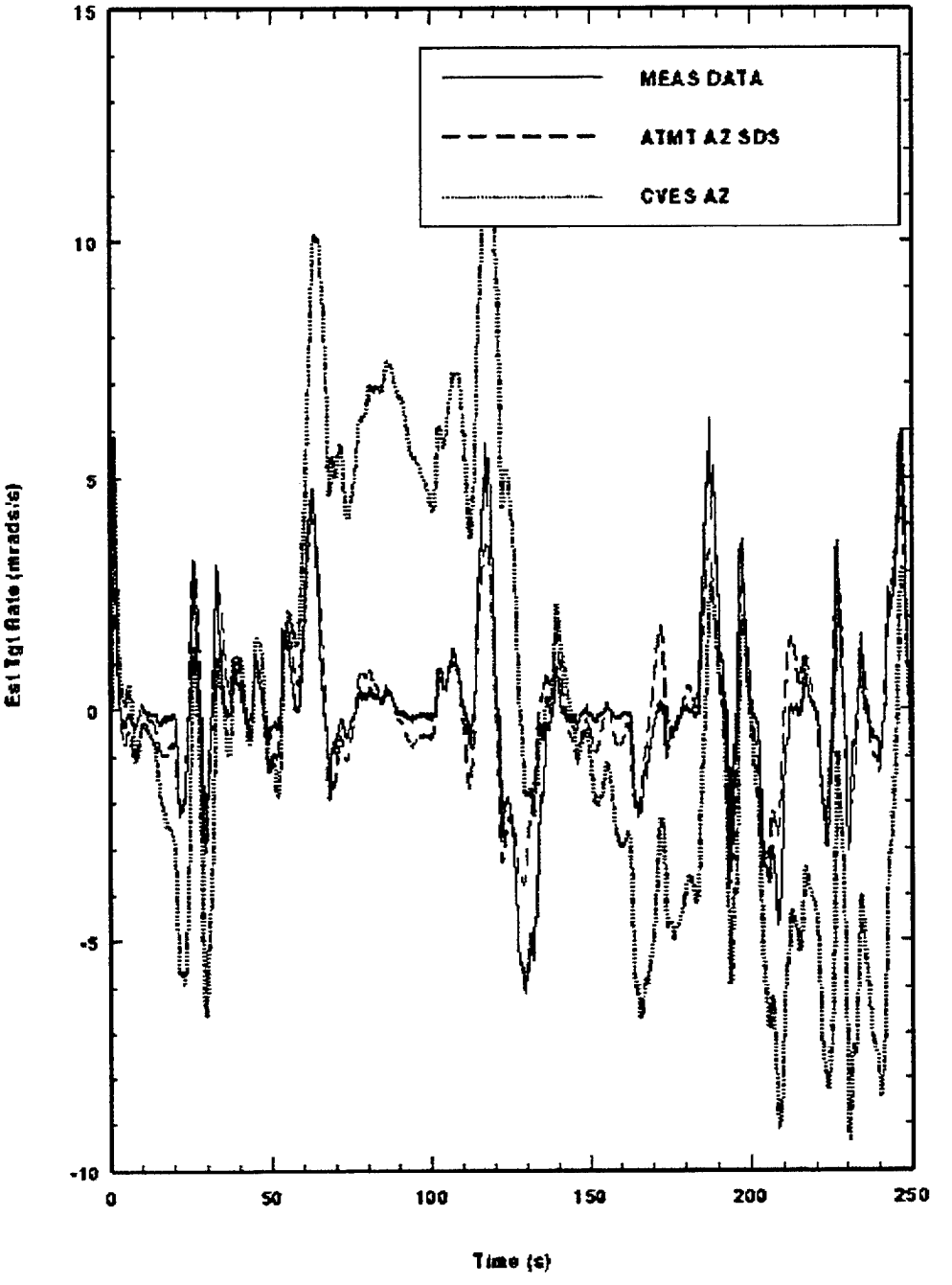

Figure 9. Comparison of ATMT Azimuth Gunner Model Output With Measured Data (target range = 2.0 km, KE round).

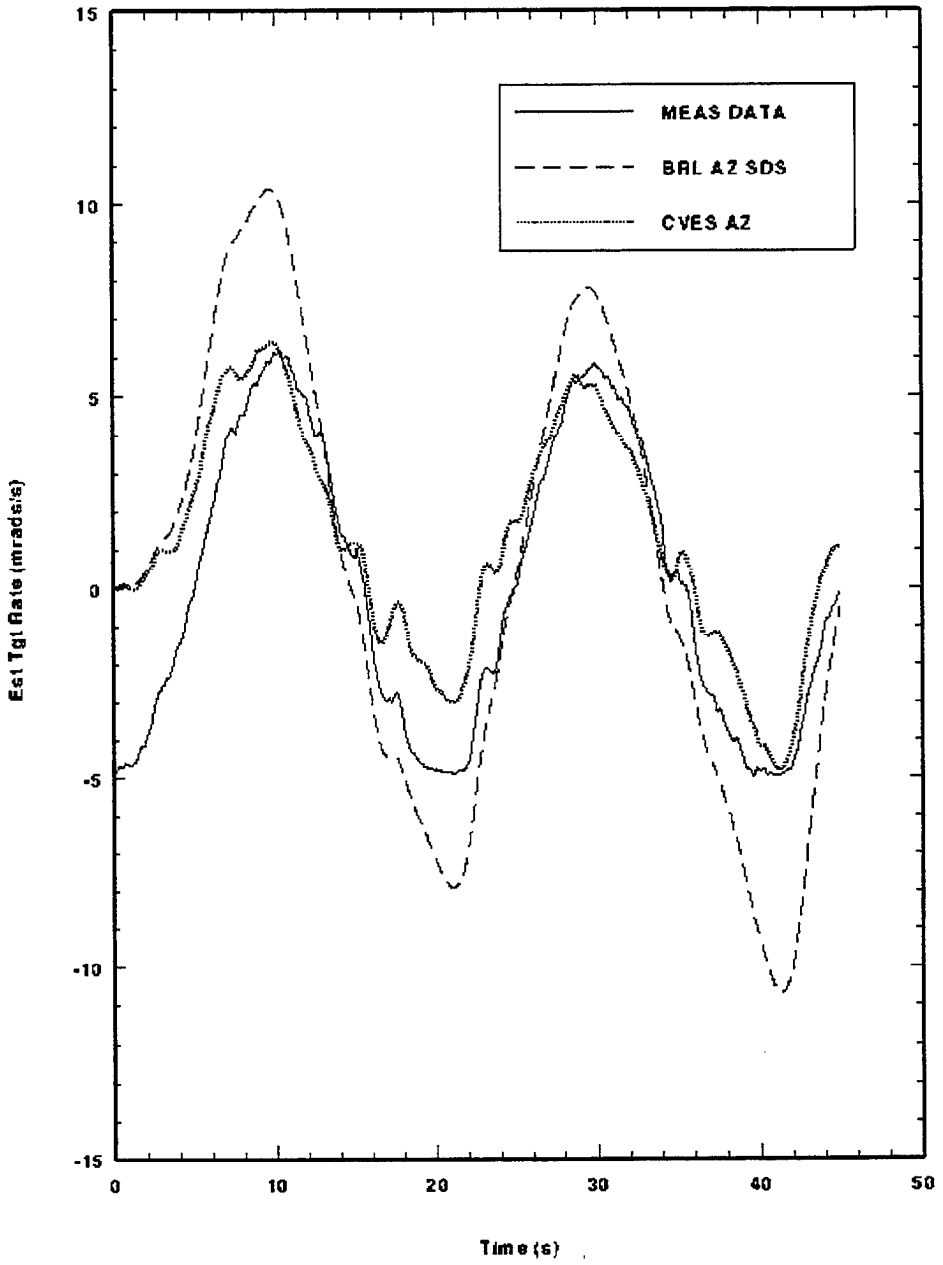

Figure 10. Comparison of BRL Azimuth Gunner Model Output With Measured Data (target range = 2.0 km, TRNG round).

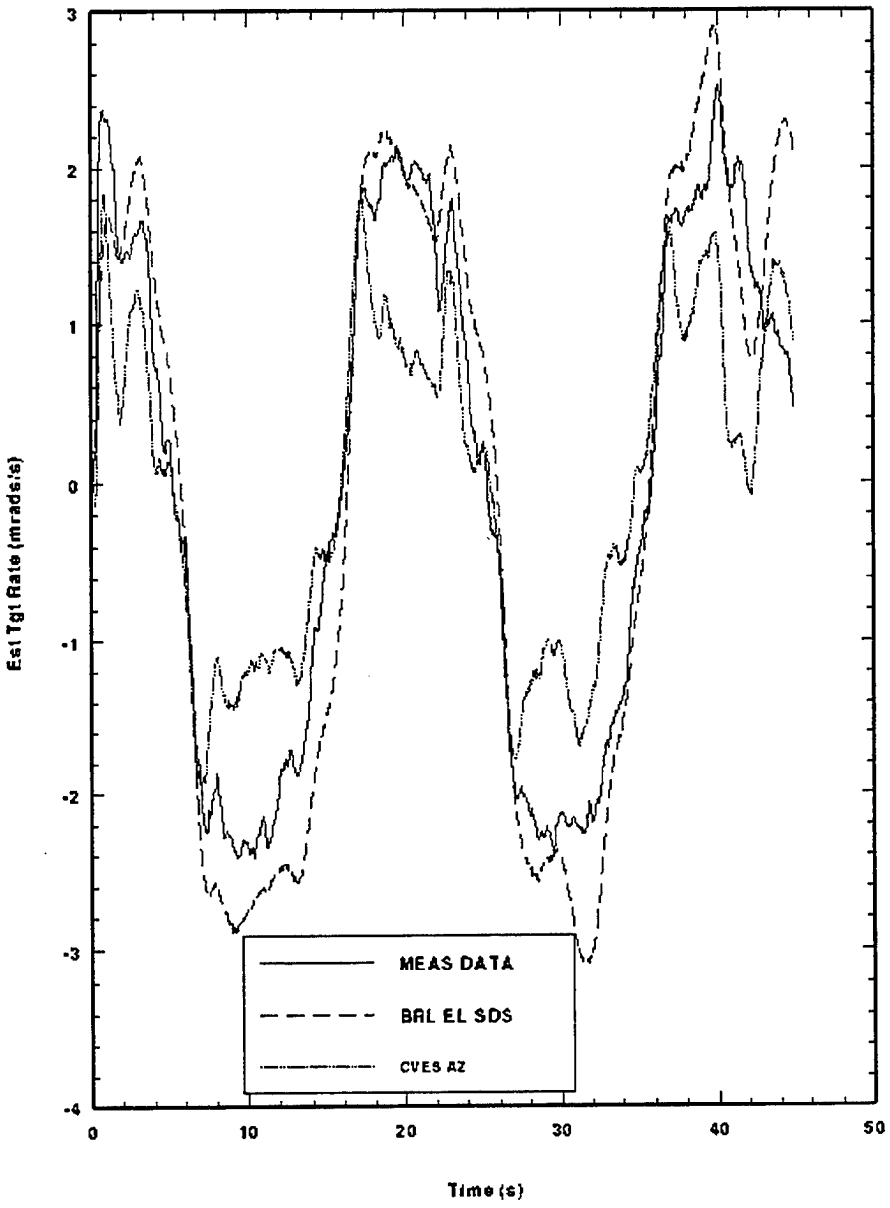

Figure 11. Comparison of BRL Elevation Gunner Model Output With Measured Data (target range = 2.0 km, TRNG round).

5. SUMMARY

The results presented in this report show that usable gunner tracking models can be developed using measured data along with the interactive system identification algorithms from the MATRIXx® software package. Depending on the identification algorithm selected, models as high as the tenth order were identified for each target path considered, but it was shown that the first order models were about as accurate as the higher order models. A first order model was developed for each of the three target paths that were considered in this study.

It was shown that for two of the three target paths tracked, the gunner models developed using the techniques discussed in this report were more accurate than the existing gunner models that are presently being used in CVES. This was especially true for the gunner model developed when the random ATMT lateral target path was tracked. The newly developed model was about six times more accurate than the CVES azimuth model in predicting the gunner output. The other model that was more accurate than an existing CVES model was the gunner model developed for tracking the BRL vertical path. It was 27% more accurate in predicting the gunner output.

On the other hand, the model developed for tracking the BRL lateral target path was shown to be about 51% less accurate than the CVES azimuth model. This was the result of using the averaging process in developing the model. If the output of each individual model, rather than the output of the average model, were compared to the output of the CVES azimuth model, the MATRIXx®-identified models would be as accurate as the CVES azimuth model when the BRL lateral target path is tracked. As mentioned in Section 2, it is not practical to use a separate model in CVES for each combination of range and round; there would be too many gunner models from which to choose.

These newly developed models are simpler in their structure than the existing CVES models. The new models are first order lag-lead networks with a gain that varies as a function of range. The CVES azimuth gunner model consists of a time delay, a gain that varies as a function of range, an integrator, a lag-lead network, and a quadratic filter. The CVES elevation gunner consists of a time delay, a gain that varies as a function of range, and a first order low pass filter.

The M1A1 gunner models developed for tracking the ATMT lateral target path and the BRL vertical target path have been installed in CVES. However, they should only be used with the M1A1 CVES. These gunner models were observed to depend on the target path, and they may depend on the weapon system as well. The weapon system dependency will not be known until gunner models are developed for the BFVS-A3. BFVS-A3 gunner models will be developed

for CVES using the techniques discussed in this report once the tracking error and estimated target rate data become available for this weapon system.

The M1A1 CVES user should select the ATMT lateral target path gunner model if the target path to be considered tends to be random and has a frequency content similar to that of the ATMT lateral path. Likewise, the BRL vertical path gunner model should be selected if the target vertical path to be considered tends to be like the BRL vertical path. If significantly different target paths are to be considered, then additional gunner models should be developed.

The existing CVES gunner models have been retained in the simulation and should be used with the BFVS-A3 CVES and the different target paths until the additional gunner models are developed and installed in CVES.

Although a formal verification of the M1A1 CVES with the new gunner models has not yet been conducted, initial indications are that the CVES tracking error output is now in better agreement with measured data.

As a result of this effort and the future effort to identify BFVS-A3 gunner models, a test conductor running a test in the VPG and using CVES will have the capability to select a more appropriate gunner model in addition to selecting the other available options. The other available user options that have been built into CVES include the selection of target range, target path, vehicle motion, ammunition, fire control configuration, and the type of turret and gun drives.

6. REFERENCES

Corcoran, P. E., and T. R. Perkins, "A Comparison of ARL's M1A1 Engineering Simulation results With Actual Test Results." ARL-MR-347, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, March 1997.

Integrated Systems, Inc. (revised January 1996), Xmath Interactive System Identification Module, Part Number 000-0027-002, Santa Clara, CA: Author.

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13. ABSTRACT *(Maximum 200 words)*

During fiscal years 1998 and 1999, an effort was conducted as part of a technology program annex with the U.S. Army Test and Evaluation Command to develop gunner tracking models for the U.S. Army Research Laboratory's Combat Vehicle Engineering Simulation (CVES). CVES contains engineering models of the fire control system, chassis-suspension, and the gunner for the M1A1 combat tank and the A3 version of the Bradley fighting vehicle system. This effort addresses the gunner model for the M1A1.

Gunner models were developed using the Xmath™ interactive system identification algorithms from the MATRIXx® software package along with measured gunner tracking error and estimated target rate data (gunner handle control output).

The resulting gunner tracking models are shown to be more accurate than the existing gunner tracking models used in CVES for two of the three maneuvering target paths that were considered in this study. Furthermore, the results demonstrate that usable models can be developed using the techniques discussed in this report.

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