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**FEASIBILITY STUDY OF VARIANCE REDUCTION
IN THE THUNDER CAMPAIGN-LEVEL MODEL**

THESIS

Earl M. Bednar, 1st Lieutenant, USAF

AFIT/GOR/ENS/05-01

**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY**

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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AFIT/GOR/ENS/05-01

**FEASIBILITY STUDY OF VARIANCE REDUCTION
IN THE THUNDER CAMPAIGN-LEVEL MODEL
THESIS**

Presented to the Faculty
Department of Operational Sciences
Graduate School of Engineering and Management
Air Force Institute of Technology
Air University
Air Education and Training Command
In Partial Fulfillment of the Requirements for the
Degree of Master of Science in Operations Research

Earl M. Bednar, MS

1st Lieutenant, USAF

March 2005

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**FEASIBILITY STUDY OF VARIANCE REDUCTION
IN THE THUNDER CAMPAIGN-LEVEL MODEL**

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Approved:

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Abstract

As an Air Force Chief of Staff endorsed topic, Air Force Studies and Analyses Agency (AFSAA) requested an effective and efficient way to reduce the variance in analysis results from THUNDER. THUNDER is a large-scale discrete event simulation of campaign-level military operations and is used to examine issues involving the utility and effectiveness of air and space power in a theater-level, joint warfare context. Given the large number of stochastic components within THUNDER, results are produced with highly variable measures of effectiveness (MOEs), causing difficulties in evaluating alternative force structures, weapon systems, etc.

This work responds to AFSAA's request by examining the application of Common Random Numbers (CRN), Antithetic Variates (AV), Control Variates (CV), and a combination of AVs and CVs and a combination of CRNs and CVs. The difference between the normal and variance reduction technique halfwidths for 95% confidence intervals were examined. Analysis of the correlation between MOEs and the random inputs in the CV technique gave insight into the workings of THUNDER. A new, state of the art combined multiple recursive generator was incorporated into THUNDER to synchronize the random inputs for CRN and AV. The result is methodology for implementing all four variance reduction techniques.

AFIT/GOR/ENS/05-01

For My Wife and Son

Acknowledgments

I have dedicated this thesis to my wife and my son. For without them I surely would be lost. My wife keeps me on track and nourishes me with encouragement and love. My son sustains my youth and enthusiasm and is a constant reminder of what life is all about. To them I am eternally grateful.

This thesis could not have been completed without the effort from a number of people to whom I would like to express my sincere appreciation. First, I like to thank my advisor Dr. Kenneth Bauer for your words of encouragement and thoughtful insight. Next, I would like to thank my reader Dr. John O. Miller for keeping me working and always expecting more. I would also like to thank Dr. Phillip Amburn and Jamie Moyers from the ASC MSRC for their tireless effort in getting this version of THUNDER running at the ASC MSRC and setting up the divide and conquer web interface to work with the new version of THUNDER. Another thanks goes out to CACI for their part in setting up the new THUNDER on high performance computing resources at the ASC MSRC. Last but definitely not least; I would like to thank all of my friends at AFIT with whom I have shared the highs and lows with here at AFIT. Thank you for just being there.

Earl M. Bednar

Table of Contents

	Page
Abstract.....	iv
Acknowledgments.....	vi
Table of Contents	vii
List of Figures.....	x
List of Tables.....	xii
Acronyms and Useful Definitions	xv
1. Introduction.....	1.1
1.1. Background.....	1.1
1.2. Problem Statement.....	1.2
1.3. Research Objective	1.2
1.4. Research Focus	1.3
1.5. Methodology.....	1.3
1.6. Aeronautical Systems Center Major Shared Resource Center	1.4
1.7. Assumptions and Limitations	1.4
1.8. Overview.....	1.5
2. Literature Review.....	2.1
2.1. Combat Simulation	2.1
2.2. THUNDER	2.2
2.2.1. Input.....	2.5
2.2.2. Output.....	2.6
2.2.3. Previous THUNDER Studies.....	2.7
2.3. SIMSCRIPT II.5	2.9
2.4. Variance Reduction Techniques	2.10
2.4.1. Control Variates.....	2.11
2.4.2. Common Random Numbers.....	2.17
2.4.3. Antithetic Variates.....	2.19
2.4.4. Control Variates and Antithetic Variates.....	2.20
2.4.5. Control Variates and Common Random Numbers.....	2.23
2.4.6. Other Techniques.....	2.24

	Page
2.4.7. Previous Variance Reduction Studies.....	2.25
2.5. Random Number Generator.....	2.26
2.6. Major Shared Resource Center and Divide and Conquer.....	2.29
2.7. Matlab and Regression.....	2.29
2.8. Analysis.....	2.31
2.8.1. Confidence Intervals.....	2.31
2.8.2. Determining the Number of Replications.....	2.32
2.8.3. Paired-t Confidence Interval.....	2.32
2.8.4. Bonferroni Inequality.....	2.33
3. Methodology.....	3.1
3.1. Research Objective.....	3.1
3.2. Model Selection for THUNDER Analysis.....	3.1
3.3. Measure of Effectiveness Selection.....	3.2
3.4. Parsing THUNDER reports.....	3.4
3.5. Control Variates.....	3.9
3.6. Common Random Numbers.....	3.15
3.7. Antithetic Variates.....	3.16
3.8. Integrated Control and Antithetic Variates.....	3.17
3.9. Integrated Control Variates and Common Random Numbers.....	3.17
3.10. Divide and Conquer and the Major Shared Resource Center.....	3.18
3.11. Analysis.....	3.19
4. Analysis.....	4.1
4.1. Control Variates.....	4.1
4.1.1. Replications vs. Variance Reduction Technique.....	4.2
4.1.2. Variance Reduction Technique to Number of Replications.....	4.6
4.1.3. Control Variate Insight.....	4.7
4.1.4. Replication Speed With And Without Generating Control Variates.....	4.10
4.2. Common Random Numbers.....	4.11
4.2.1. Normal to Variance Reduction Technique.....	4.12
4.2.2. Common Random Numbers Insights.....	4.13
4.3. Antithetic Variates.....	4.15
4.3.1. Normal to Variance Reduction Technique.....	4.16
4.3.2. Variance Reduction Technique to Number of Replications.....	4.17
4.3.3. Antithetic Variates Insights.....	4.19
4.4. Control Variates and Antithetic Variates.....	4.19
4.4.1. Normal to Variance Reduction Technique.....	4.20
4.4.2. Variance Reduction Technique to Number of Replications.....	4.22
4.4.3. Combined Antithetic Variate and Control Variate Insight.....	4.24
4.5. Control Variates and Common Random Numbers.....	4.27

	Page
4.5.1. Normal to Variance Reduction Technique	4.28
4.5.2. Combined Control Variate and Common Random Number Insight.	4.30
4.6. Random Number Generator Comparison	4.31
4.6.1. Original vs. New (not synchronized) Random Number Generator.	4.32
4.6.2. Original vs. New (synchronized) Random Number Generators.....	4.34
4.6.3. New (not synchronized) vs. New (synchronized) Random Number Generators.....	4.36
5. Conclusion	5.1
5.1. Conclusions.....	5.1
5.1.1. Control Variates.....	5.1
5.1.2. Common Random Numbers.	5.2
5.1.3. Antithetic Variates.....	5.2
5.1.4. Control Variates and Antithetic Variates.....	5.3
5.1.5. Control Variates and Common Random Numbers.....	5.3
5.1.6. Random Number Generator.....	5.3
5.2. Recommendations for Further Work or Study.....	5.4
5.2.1. Further THUNDER Work.....	5.4
5.2.2. Further THUNDER Study.....	5.5
Appendix A: THUNDER Report Example (1 Full Day)	A.1
Appendix B: Table of Distribution Expected Values	B.1
Appendix C: The Modified and Added Files	C.1
Appendix D: CONTROL.DAT File	D.1
Appendix E: Example SIMSCRIPT II.5 Code AIR070.SIM (Original)	E.1
Appendix F: Example SIMSCRIPT II.5 Code AIR070.SIM (Modified)	F.1
Appendix G: MRG32k3a Routines and Variables (18)	G.1
Appendix H: CHARACTERISTICS OF VRTs (6).....	H.1
Appendix I: SQUADRON.DAT File Example (33)	I.1
Bibliography	BIB.1
Vita.....	VITA.1

List of Figures

Figure	Page
Figure 2.1: Combat Modeling Hierarchy (26)	2.2
Figure 2.2: THUNDER User Base (13).....	2.5
Figure 3.1: Parsing Script Flow Chart	3.5
Figure 3.2: Example of earltally.txt File.....	3.6
Figure 3.3: Logical Expression Example (Original).....	3.10
Figure 3.4: Logical Expression Example (Modified)	3.11
Figure 3.5: Random Variate Subroutine Call Example (Original)	3.12
Figure 3.6: Random Variate Subroutine Call Example (Modified).....	3.13
Figure 3.7: Divide and Conquer Flow Diagram (29).....	3.19
Figure 4.1: BLUE Flown per Planned Sortie Confidence Intervals	4.4
Figure 4.2: MIG-23 Losses per Sortie Confidence Intervals.....	4.5
Figure 4.3: Replication Completion Difference Confidence Interval.....	4.10
Figure 4.4: MIG-23 Losses per Sortie Value Difference Confidence Intervals	4.13
Figure 4.5: MIG-29 Losses per Sortie Value Difference Confidence Intervals	4.13
Figure 4.6: Original vs. New (not synchronized) Random Number Generator Confidence Intervals.....	4.34
Figure 4.7: Original vs. New (synchronized) Random Number Generator Confidence Intervals.....	4.36

Figure	Page
Figure 4.8 New (not synchronized) vs. New (synchronized) Random Number Generator Confidence Intervals	4.38

List of Tables

Table	Page
Table 2.1: Parameter Specifications for Stepwisefit (23)	2.31
Table 3.1: Measure of Effectiveness Table.....	3.3
Table 3.2: Random Distribution Decodes.....	3.6
Table 3.3: Example of earlally.txt Final Product.....	3.7
Table 3.4: Example of AW-3 Final Product.....	3.8
Table 3.5: Experiment Settings.....	3.20
Table 4.1: Control Variate Experiment Settings.....	4.2
Table 4.2: Control Variate Halfwidth Reduction.....	4.3
Table 4.3: Control Variate RSquared.....	4.4
Table 4.4: Absolute Percent Change In Means.....	4.5
Table 4.5: Number of Replications Required to Achieve Control Variate Reduction	4.6
Table 4.6: Control Variate Statistically Significant Controls	4.8
Table 4.7: Control Variate Purpose of Statistically Significant Controls.....	4.9
Table 4.8: Common Random Number Experiment Settings	4.11
Table 4.9: Common Random Number Halfwidth Reduction.....	4.12
Table 4.10: Common Random Number Configuration Decision	4.14
Table 4.11: Antithetic Variate Experiment Settings.....	4.15
Table 4.12: Antithetic Variate (300 Replication) vs. Replication Reduction.....	4.16
Table 4.13: Antithetic Variate (150 Replication) vs. Replication Reduction.....	4.17

Table	Page
Table 4.14: Replications Needed to Achieve Antithetic Variate Reduction (300 Replications)	4.18
Table 4.15: Replications Needed to Achieve Antithetic Variate Reduction (150 Replications)	4.19
Table 4.16: Antithetic Variate / Control Variate Experiment Settings.....	4.20
Table 4.17: Control Variate and Antithetic Variate (300 Replication) vs. Replication Reduction	4.21
Table 4.18: Control Variate and Antithetic Variate (150 Replication) vs. Replication Reduction	4.22
Table 4.19: Replications Needed to Achieve Control Variate and Antithetic Variate Reduction (300 replications)	4.23
Table 4.20: Replications Needed to Achieve Control Variate and Antithetic Variate Reduction (150 replications)	4.24
Table 4.21: Antithetic Variate and Control Variate Statistically Significant Controls Table (150 Replications)	4.25
Table 4.22: Antithetic Variate and Control Variate Purpose of Statistically Significant Controls	4.26
Table 4.23: Control Variate and Common Random Number Experiment Settings	4.28
Table 4.24: Control Variate and Common Random Number Halfwidth Reduction	4.29
Table 4.25: Control Variate Only Halfwidth Reduction.....	4.30
Table 4.26: Control Variate and Common Random Number Configuration Decision .	4.31
Table 4.27: Random Number Experiment Settings	4.32

Table	Page
Table 4.28: Original vs. New (not synchronized) Random Number Generator	4.33
Table 4.29: Original vs. New (synchronized) Random Number Generator	4.35
Table 4.30: New (not synchronized) vs. New (synchronized) Random Number Generator	4.37

Acronyms and Useful Definitions

<u>Acronym</u>	<u>Definition</u>
AFIT	Air Force Institute of Technology
AFSAA	Air Force Systems and Analysis Agency
AFSAT	Air Force Standard Analysis Toolkit
ASC	Aeronautical Systems Center
AV	Antithetic Variate
AW	Air War
CC	Ground Combat Cycle
CMGR	Congruential Multiple Recursive Generator
CRN	Common Random Number
CV	Control Variate
DAC	Divide and Conquer
DoD	Department of Defense
FLOT	Forward Line of Troops
FPS	Flown per Planned Sortie
GUI	Graphical User Interface
HPC	High Performance Computing
LCG	Linear Congruential Generator
LPS	Losses per Sortie
MATLAB [®]	Matrix Laboratory
MCA	All Pairwise Multiple Comparisons

<u>Acronym</u>	<u>Definition</u>
MCB	Multiple Comparisons with the Best
MCC	Multiple Comparisons with a Control
ME	Refers to the Middle East THUNDER scenario
MOE	Measure of Effectiveness
MRG32k3a	The name of the congruential multiple recursive generator used in L'Ecuyers random number generation package
MSRC	Major Shared Resource Center
RNG	Random Number Generator
SMG	Square Miles Gained
VRT	Variance Reduction Technique

FEASIBILITY STUDY OF VARIANCE REDUCTION IN THE THUNDER CAMPAIGN-LEVEL MODEL

1. Introduction

1.1. Background

Over the years, the Department of Defense (DoD) has been tasked to continue to be the leader in military strength and technology, with less and less funding. One way the DoD has done this is through the use of stochastic combat simulation. Stochastic combat simulation is a way to model how the input parameters affect a specified measure of effectiveness (MOE) in a combat situation. To do this, an analyst uses simulation software to construct a combat simulation by assigning probabilities to weapons systems and logical flow in order to determine the interaction of the simulated combat forces. The results from a stochastic combat simulation are point estimates because they rely on a series of pseudo-random numbers. These pseudo-random numbers are used to model the randomness of a system. This randomness can greatly affect the simulation results, leading to a range of estimates.

There are many known ways to reduce the variance in the MOEs. The most common method is to increase the number of replications completed. This method can prove to be inefficient due to the size of the simulation. Even with the speed of today's computers, some of the larger simulations can take hours or even days to complete one replication. Therefore, an increase in replications may be unacceptable. Other methods

of reducing the variance are called variance reduction techniques (VRTs). These techniques use knowledge of the workings of computer simulations and mathematical techniques to reduce the variance without increasing the number of replications (20:581).

The DoD uses a variety of large, stochastic combat simulations to conduct various analyses of interest. These interests vary from acquisition to planning to training. One of the large, stochastic combat simulations used by the Air Force (AF) is THUNDER. THUNDER is a stochastic, two-sided, analytical simulation of campaign-level military operations developed in the 1980s under the guidance of the Air Force Studies and Analyses Agency (AFSAA). The simulation was designed and built expressly to examine issues involving the utility and effectiveness of air and space power in a theater-level, joint warfare context.

1.2. Problem Statement

Given the large number of stochastic components within THUNDER, the model often produces MOEs with significant variance. This variance often causes difficulties in evaluating alternative force structures, weapon systems, etc. With time sensitive analysis and long replication times, AFSAA is looking for an effective and efficient way to reduce the variance in the results from the THUNDER campaign-level model.

1.3. Research Objective

The objective of this research will be to study the use of variance reduction techniques on THUNDER. The study of existing variance reduction techniques will determine which, if any, are effective and efficient.

1.4. Research Focus

This research examines the use of several classic VRTs. The primary focus of this research identified potential control variates (CV), within the model, that can be used to reduce the variance in the output. Then using these potential control variates, determine how much each potential control variate influences the MOE variance. The areas are also checked to find out if there is any other information that can be gleaned from the relationship between the identified control and the simulation MOE.

A secondary focus of this research examines the use of two other classic VRTs. The second VRT applied is common random numbers (CRN). CRN is probably the second most popular way of reducing variance, following increasing the number of replications. It is primarily used when trying to identify differences between simulation configurations. The basic idea is to reduce noise, generated by the random inputs, in the variation of the system. The third VRT applied is antithetic variates (AV). AV attempts balance out any radically low or high random input. Also, the application of combining AV with CV is reviewed.

1.5. Methodology

In the control variate technique, the primary focus is in the generation of random variates throughout a simulation. Initially, the random variate averages are generated and stored. The differences in the simulated mean and expected value are regressed against the simulation MOEs. This identifies which random variates are influential to the selected MOEs.

To use the CRN technique, the pseudo-random number calls need to have their own random number stream. THUNDER already has a way to assign different random

number streams. The problem with THUNDERs current RNG is that there are only 10 streams to choose from and 245 different random number calls. Therefore, a new random number generator is needed to allow for all the random number calls to have its own stream. In this research, the random number generator suggested by Pierre L'Ecuyer, Richard Simard, E. Jack Chen, and W. David Kelton (18) was added to THUNDER.

1.6. Aeronautical Systems Center Major Shared Resource Center

Simulation replications for this research were performed with cooperation with the Aeronautical Systems Center (ASC) Major Shared Resource Center (MSRC). The ASC MSRC is a computational science facility. It supports various DoD research initiatives including development, test, and evaluation. As part of the DoD's High Performance Computing (HPC) Modernization Program, the ASC MSRC uses high performance computing research and visualization. Access to the ASC MSRC HPC resources was facilitated by use of the Divide and Conquer (DAC) system. The DAC system is fronted by a web interface that assists in configuring experiments and has direct access to HPC resources.

1.7. Assumptions and Limitations

The major limitation of this research occurs due to the classification of the THUNDER model databases. Since most THUNDER model databases represent a real battle plan, implement new military technology, or contain specific data on current military systems, most all THUNDER model databases are classified to some level. Therefore, the only unclassified model databases available are the three notional model databases distributed with THUNDER. The model database used in this research is the

Middle East (ME) scenario. Assuming the VRT affects THUNDER and does not rely on the scenario, the VRT can be used on any other THUNDER scenario study.

1.8. Overview

There are five chapters in this research. Chapter 1, the Introduction, contains background information, problem statement, research objective, a synopsis of the methodology, and the assumptions and limitations of the research. Chapter 2, the Literature Review, contains descriptions of THUNDER, other THUNDER work, CVs, CRNs, AVs, other VRTs, and analysis techniques. Chapter 3, the Methodology, discusses how CVs, CRNs, and AVs are applied in THUNDER. Chapter 4, Results and Analysis, presents the output of the selected ME scenario MOEs and the results from the application of CVs, CRNs, and AVs. Chapter 5, Conclusions, is a look at the analysis done in the previous chapter with recommendations for future work in the application of VRTs and THUNDER.

2. Literature Review

This chapter contains background information on software, models, techniques and services used in completing this research. It begins with a discussion on combat simulations, specializing in the THUNDER campaign level combat simulation. It continues with a description of THUNDER's computer language, SIMSCRIPT II.5. Next, there is a lengthy section on variance reduction techniques. This section reviews Control Variates, Common Random Numbers, and Antithetic Variates in depth, while giving a brief overview of other techniques. To close this section, there is a review of other variance reduction studies. Next, the random number generator added to THUNDER for use with CRN is described. Following this, is a short description of the ASC MSRC's Divide and Conquer system used to replicate the runs. This chapter ends with an overview of variance and confidence intervals.

2.1. Combat Simulation

“Simulation of large-scale combat models contribute useful insights for many military decision problems.”(14:1-1) There are many reasons why a system is modeled by computer simulation. For instance, a system may be too difficult or expensive to alter, the system may not exist, or even unacceptable to simulate in real life. In combat simulations, the latter is probably the case. It would be unethical to start real combat merely to test a new weapon system. The goal in the design of combat models is to represent warfare as accurately as possible, because results from combat simulation can guide national defense and other policy decisions.

There are many different levels of combat modeling. They range from engineering to campaign level simulations, see Figure 2.1 (26). A campaign level simulation encompasses a whole campaign and covers many different elements. The sheer volume of entities would make it difficult to simulate each entity interaction. Therefore, they are performed with low resolution and aggregation. This aggregation means that each entity is not simulated but is replaced by probabilities and percentages. This allows a large campaign level simulation to run in an acceptable time frame, at the cost of losing output resolution.

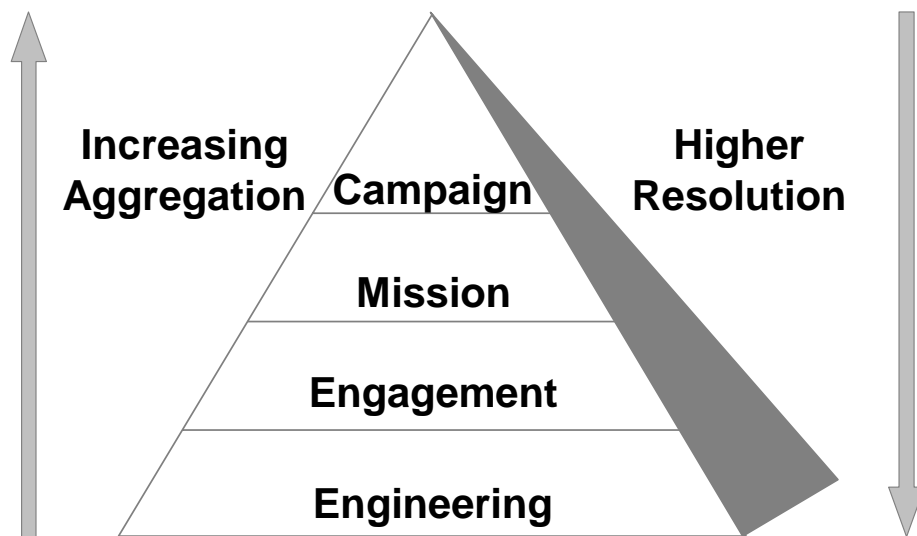


Figure 2.1: Combat Modeling Hierarchy (26)

2.2. THUNDER

This research is a study on THUNDER, a large stochastic, two-sided, constructive simulation that has been operational since 1986. It was developed to examine the utility and effectiveness of air and space power in at a campaign-level and models joint military operations at the campaign-level. The Air Force Studies and Analyses Agency (AFSAA)

sponsored the development of THUNDER. The following material is obtained from the THUNDER web pages (13) and Volume One of the THUNDER documentation (35).

THUNDER is designed for analytical flexibility, accessibility, and ease of use. It operates in a UNIX environment and is written in SIMSCRIPT II.5, a simulation programming language. SIMSCRIPT II.5 is ideal for the creation of large scale, discrete-event simulations. To aid the analyst, the distribution of THUNDER comes with in-depth documentation and source code, allowing modification at the programming level. The source code of THUNDER, alone, consists of around 360,000 lines of codes spread across over 1,500 routines.

THUNDER operates at multiple levels of detail. It models air operations at a high level of detail, with the ability to simulate 27 different air missions. While it can simulate air operation at a high level of detail, it models ground operations at a medium level of detail, focusing on ground combat, logistics, terrain, C3I, and mobility.

To assist the user and speed up replications, THUNDER automatically generates its own Air Tasking Orders (ATOs) and Intelligence Tasking Orders (ITOs), based on theater-level apportionment and target priorities. It also uses a deterministic time stepped ground operations model based on the Center for Army Analysis Concept Evaluation Model (CEM) and its Attrition Calibration Methodology (ATCAL).

THUNDER can be run in two modes: analytical and wargame. The analytical mode focuses on the contribution of systems, capabilities, forces and employment concepts. It is run in a batch mode and delivers results that can be identified by replication or as a mean across replications with confidence intervals. When run in batch mode, THUNDER starts the following random number stream where the previous stream

stops. The wargame mode supports a user interaction in a game like atmosphere, where a player dynamically influences the outcome of a run.

As a member of the Air Force Standard Analysis Toolkit (AFSAT), THUNDER supports senior decision makers (Figure 2.2) in matters of policy, acquisition and operations. Typically, these customers require precise and timely analysis. The analysis applications include: exploration of readiness, modernization, force structure, and sustainability issues; comparison of alternative courses of action (ACA); assessments of evolving capabilities, alternative strategies and potential operational concepts; and the facilitation of senior staff training through wargaming.

THUNDER user base			
US Air Force	Joint/ Other Services	Allied Militaries	Industry
AFSAA/SAAC AFSAA/SAAI	Joint Strike Fighter Program Office	French Air Force	Boeing
ACC/XP-SAS	Naval Air Warfare Center [Aircraft Division]	RAF Air Warfare College	Boeing North American
HQ AF/XPY		RAF Air Warfare Center	Lockheed Martin / Atlanta
ASC/EN		ROK Air Force	Lockheed Martin / Fort Worth
Air Force Wargaming Institute		Lockheed Martin / Dallas	
ESC/DIS		Northrop Grumman Corporation	
SMC/XRE		Analysis International Ltd.	
SWC/AEWF		SPA	
AFIT/ENS		Veridian	

Figure 2.2: THUNDER User Base (13)

2.2.1. Input.

THUNDER is a data driven simulation. Therefore, the individual model parameters are held in a data structure or database and can be changed. THUNDER uses 99 text files as a model database. These files contain all the information relating to the

entities, map, and course of action. THUNDER also allows the user to use toggles to tailor how a model is run. The use of the databases allows for sharing of data and minimizing storage space. It also aids in portability between systems and even sharing between users.

2.2.2. Output.

THUNDER comes with three types of post-processors to handle the hundreds of different MOEs available. The first is a comprehensive suite of text post-processors. They provide the user with a means to extract information from a simulation. THUNDER uses an input file to toggle, which postprocessors are run and which output files are requested. An example of one of the output files is in Appendix (A). The second type is a graphical post processor that allows the user to step through a single replication graphically. It contains a situation map and it depicts the locations of military units for both sides over half day increments. Third, THUNDER comes with a post processor that creates user specified graphs.

THUNDER contains post processors that can produce many different MOEs. To obtain the data for a MOE, the user selects one or more reports of interest to produce. Three reports were chosen for this project. The three reports are CC-4 (FLOT Movement), AW-3 (Aircraft Loss Summary), and AW-5 (Sortie Generation). All three are contained in a single output file named *reports.std* located in the REPORTS subdirectory. When running multiple replications of a thunder model, there will be a number following the reports name. The number references the replication number from which the file was created. The *reports.std* file combines all three reports and organizes

them in time order, then report name order, and then order of side. Please refer to Appendix (A). It contains the output from the entire first day of a replication.

The CC-4 report is a Ground Combat Cycle report. It displays FLOT movement in square miles gained or lost by command and FLOT location in latitudes and longitudes by 12-hour increments. The AW-3 report is an Air War report. It contains losses and sorties by aircraft for each day. The AW-5 report also is an Air War report. It contains planned and flown sortie data for each mission type by base and squadron for each day.

2.2.3. Previous THUNDER Studies.

THUNDER is a large stochastic combat simulation. The size and complexity of THUNDER has made it a prime simulation for study. Over the years there have been efforts to analyze the inner workings of THUNDER. Much of this work has been done here at the Air Force Institute of Technology (AFIT). Below is a sampling of previous THUNDER research at AFIT.

Major David A. Davies performed a sensitivity analysis to command and control (C2) inputs in THUNDER. He employed design of experiments (DOE) to identify statistically significant variables to specified outputs. Then response surface methodology (RSM) was used to generate a response surface of the relationships between the input and output variables. Major Davies also demonstrated the ASC MSRCs capability to perform parallel processing, completing 1,560 THUNDER runs for the analysis. Normally this would have taken around 3 months, but it was accomplished at the ASC MSRC in around 3 days using parallel processing. (5)

Captain Michael R. Farmer studied how to quickly analyze the effects of changing force structure with THUNDER. The modifications Capt Farmer made

consisted of limiting the amount of primary tactical aircraft. Capt Farmer used RSM to create metamodels of THUNDER, which in turn could be used to provide a quick answer to a change in force structure. He also used factor analysis (FA) to reduce the dimensionality of data sets and determine relationships between MOEs. (8)

Captain Steven L. Forsythe applied RSM to a THUNDER scenario in order to optimize the air apportionment. Captain Forsythe created a response surface and used a steepest-gradient search to find the optimal aircraft apportionment for MOEs such as FLOT movement and attrition. In addition, he demonstrated how RSM could provide useful information as to how the algorithms used by TAC THUNDER, interact to simulate the combat environment. (9)

Captain Brian M. Godfrey compared five Air Expeditionary Force (AEF) packages. Captain Godfrey used THUNDER to obtain most of the MOEs used in the study. The study results in a methodology for modeling AEF packages using THUNDER and a methodology to analyze the results. (11)

Major James B. Grier developed a tool to capture the cost and capabilities of alternative force structures. The tool uses FA and RSM to link monetary cost to MOEs. USAF/XPY directed Major Grier to develop his tool using THUNDER. His research focused on the Southwest Asia scenario developed by HQ ASC/XR. (12)

Captain Francine N. Nelson conducted a validation assessment of THUNDER 6.5's Intelligence, Surveillance, and Reconnaissance (ISR) Module. This study provides an overview of the ISR process, level of aggregation, possible problem areas, and basis for ISR improvement within THUNDER. This study also presents a sensitivity analysis

of the ISR parameters relating to the Quality, Quantity, and Timeliness of ISR. DOE and linear regression were used to develop a response surface for the sensitivity analysis. (27)

Captain Timothy S. Webb examined the overall model variability, output interrelationships, and sensitivity to input parameters in THUNDER. The examination of the model variability focused on the replication requirements to obtain specified measures of outcome (MOOs). The application of principal component analysis (PCA) and FA were used to examine output interrelationships. The input parameters were tested for significance and consistency. (42)

2.3. SIMSCRIPT II.5

To understand the inner workings of a simulation, one must learn the language it is programmed in. THUNDER is programmed in CACI's SIMSCRIPT II.5. According to the SIMSCRIPT II.5 description web page at CACI, SIMSCRIPT II.5 is an easy-to-use and powerful simulation language with English-like syntax (4). The English-like syntax facilitates a more intuitive understanding of the simulation.

As a simulation language, it provides a timing mechanism and concurrent process management in addition to all the standard features of a general-purpose high-level programming language. It has preprogrammed discrete event simulation features like entities, attributes, sets, events, processes and resources. These added features are key elements of an efficient and effective simulation. SIMSCRIPT II.5 also has built in graphical capabilities, allows models to be stored as a database, is portable across a variety of platforms, and can readily interface between selected other programming languages.

There are three basic parts to the structure of a SIMSCRIPT II.5 program. They are, the main program, routines, and the preamble. The main program is the essential part. It consists of either the whole program or the starting and ending part of a program that consists of calls to one or more subroutines. The main program is where SIMSCRIPT II.5 looks for the start of the program. Routines are functions, subroutines, events or processes. They are generally used to compartmentalize the simulation code for better organization and ease of understanding the program flow, and are activated by either the main program or other routines. The preamble is where global variables are declared and constants are defined. THUNDER was developed with its own nomenclature; therefore its preamble is like a Rosetta stone. It provides the key to translate words and phrases in THUNDERs code back into a standard programming language.

SIMSCRIPT II.5 is mainly used for discrete-event and combined discrete-event/continuous simulation models. It is applied world wide in building large-scale simulations and modeling applications. Some typical SIMSCRIPT II.5 applications are seen in Telecommunications, Network analysis, Transportation, Manufacturing, Inventory control, Health care, Military operations, wargaming and logistics planning. Some organizations that use SIMSCRIPT II.5 are the Federal Aviation Administration, Saudi Aramco, Raytheon, Rolls Royce, the U.S. Army and the U.S. Air Force. (4)

2.4. Variance Reduction Techniques

A stochastic simulation, such as THUNDER, relies on input that is random and therefore produces output that is also random. This means, that since there are inputs that vary randomly from replication to replication, there will also be random variation in the

output from replication to replication. Often this variation is so large it obscures the estimates of the models MOEs. Therefore analysts have developed techniques to reduce this random variation in the output. These techniques are called variance reduction techniques (VRTs). There are many different types of VRTs and the effectiveness of each technique is dependent on the particular model and application. Three common VRTs are Control Variates (CV), Common Random Numbers (CRN), and Antithetic Variates. CV and AV are single model techniques, meaning they are applied to a single configuration of a simulation, while CRN is a multiple model technique, meaning it is applied when two or more configurations are compared. These VRTs are explained in depth below and then are followed by a quick synopsis of some other VRTs.

2.4.1. Control Variates.

In essence, control variates attempt to take advantage of any correlation between random variates in a simulation and the selected output. It is best when talking about control variates to start out with a single response and a single control. The same theory can then be extended to multiple controls. The remainder of this section is derived from notes taken from Dr. Bauer. (1:64-70.5)

Consider the case where there is only a single control. Now, assume there is a mean response of interest from the simulation called μ_Y for which Y is an estimator. Also, assume there is another output variable, X , that is correlated with the Y response and has an expected value μ_X that is known. Since X is correlated with the Y variable, it is known as the control variable. Now consider the controlled estimator $Y(b)$ given in equation (2.1) where b is a constant.

$$Y(b) = Y - b(X - \mu_X) \quad (2.1)$$

Note that $Y(b)$ is an unbiased estimator of μ_Y by equation (2.2).

$$E[Y(b)] = E[Y] - E[b(X - \mu_X)] \quad (2.2)$$

$$E[Y(b)] = \mu_Y - b(\mu_X - \mu_X) = \mu_Y \quad (2.3)$$

The variance of $Y(b)$ is given in equation (2.4).

$$\text{Var}(Y(b)) = \text{Var}(Y) + b^2\text{Var}(X) - 2b\text{Cov}(Y, X) \quad (2.4)$$

With a little manipulation of equation (2.4) it can be shown that the variance of $Y(b)$ is smaller than the variance of Y if equation (2.5) holds.

$$2b\text{Cov}(Y, X) > b^2\text{Var}(X) \quad (2.5)$$

In observing equation (2.5), it is apparent that if the variables X and Y are independent, then the $\text{Cov}(X, Y) = 0$ and it follows that there can be no reduction in variance of Y .

To find the value of b that minimizes equation (2.4), the derivative with respect to b is found.

$$\frac{\partial \text{Var}(Y(b))}{\partial b} = 2b\text{Var}(X) - 2\text{Cov}(Y, X) \quad (2.6)$$

From equation (2.6) the minimum point is found by setting the derivative to zero.

Equation (2.7) is the candidate for b that minimizes equation (2.4) thus labeled β .

$$\beta = \frac{\text{Cov}(Y, X)}{\text{Var}(X)} \quad (2.7)$$

To verify this is a minimum, the second derivative is found.

$$\frac{\partial^2 \text{Var}(Y(b))}{\partial b^2} = 2\text{Var}(X) \quad (2.8)$$

Since the variance is always positive, then equation (2.7) is the value for b that minimizes equation (2.4). Combining equation (2.4), equation (2.7), and using some simple algebra yields equation (2.9).

$$\text{Var}(Y(\beta)) = (1 - \rho_{XY}^2) \text{Var}(Y) \quad (2.9)$$

Where ρ_{XY} is the correlation coefficient between X and Y . $\text{Var}(Y(\beta))$ is the minimum variance. The controlled observations (2.10) are averaged (2.11) to obtain an unbiased estimator of μ_Y .

$$Y_i(\beta) = Y_i - \beta(X_i - \mu_X), i = 1, \dots, K \quad (2.10)$$

$$\bar{Y}(\beta) = \frac{1}{K} \sum_{i=1}^K Y_i(\beta) \quad (2.11)$$

where K is the sample size.

Since the value of β is unknown, it must be estimated. An estimate of β can be found by substituting the sample quantities into equation (2.7). This solution is the least squares solution for β . The least squares solution is also the maximum likelihood solution with the assumption of joint normality between X and Y . Equation (2.12) estimates β .

$$\hat{\beta} = \frac{\sum_{i=1}^K (Y_i - \bar{Y})(X_i - \bar{X})}{\sum_{i=1}^K (X_i - \bar{X})^2} \quad (2.12)$$

The point estimator of μ_Y is estimated by equation (2.13).

$$\hat{\mu}_Y(\hat{\beta}) = \frac{1}{K} \sum_{i=1}^K Y_i(\hat{\beta}) \quad (2.13)$$

Using regression theory an interval estimate for μ_Y can be obtained. By making the assumption of joint normality for X and Y , the conditional distribution of Y given X will be normal by equation (2.14)

$$Y | X = x \sim N(\mu_Y + \beta(x - \mu_X), \sigma_\varepsilon^2) \quad (2.14)$$

where

$$\sigma_\varepsilon^2 = \sigma_Y^2(1 - \rho_{XY}^2) \quad (2.15)$$

and

$$\sigma_Y^2 = \text{Var}(Y) \quad (2.16)$$

Since the values of the control variable X and its mean μ_X are known, then it can be seen that the conditional mean of Y given X has two terms. The terms are broken into the parameter to be estimated μ_Y and a correction term. To get the μ_Y term, the corrections need to be subtracted out as in equation (2.10). From equation (2.14), equation (2.17) can be formed.

$$Y_i = \mu_Y + \beta(X_i - \mu_X) + \varepsilon_i, 1 \leq i \leq K \quad (2.17)$$

where ε_i are the residuals and are of the form in equation (2.18).

$$\varepsilon_i \sim N(0, \sigma_\varepsilon^2) \quad (2.18)$$

Since the values of μ_Y and β are unknown, the method of least squares can be applied to solve for them. μ_Y will be the intercept and is normally distributed as in equation (2.19).

$$\hat{\mu}_Y(\hat{\beta}) \sim N(\mu_Y, \sigma_\varepsilon^2 s_{11}) \quad (2.19)$$

The value of s_{11} in equation (2.19) is the upper left hand entry in the matrix $(D^T D)^{-1}$

where D is of the form in equation (2.20).

$$D = \begin{bmatrix} 1 & X_1 - \mu_X \\ 1 & X_2 - \mu_X \\ 1 & X_3 - \mu_X \\ \vdots & \vdots \\ 1 & X_K - \mu_X \end{bmatrix} \quad (2.20)$$

To generate a confidence interval about $\hat{\mu}_Y(\hat{\beta})$, σ_ε^2 must be estimated. Since σ_ε^2 represents the variability in Y given X , the formula for the residual mean square error is used.

$$\sigma_\varepsilon^2 = \frac{\sum_{i=1}^K (Y_i - \hat{Y}_i)^2}{K - 2} \quad (2.21)$$

where

$$\hat{Y}_i(\hat{\beta}) = \hat{\mu}_Y(\hat{\beta}) + \hat{\beta}(X_i - \mu_X), 1 \leq i \leq K \quad (2.22)$$

It can be seen, from the above equations, that

$$\frac{\hat{\mu}_Y(\hat{\beta}) - \mu_Y}{\left[\frac{\sigma_\varepsilon^2 S_{11}}{K - 2} \right]^{\frac{1}{2}}} \sim t_{K-2} \quad (2.23)$$

has a Student-t distribution with $K-2$ degrees of freedom. Therefore, the confidence interval for μ_Y is given by

$$\hat{\mu}_Y \pm t_{K-2, \left(1 - \frac{\alpha}{2}\right)} \sqrt{\sigma_\varepsilon^2 S_{11}} \quad (2.24)$$

Now in simulations there are possibly more than one control for a response. Therefore, equation (2.17) is modified to be

$$Y_i = \mu_Y + \sum_{j=1}^Q \beta_j (X_{ji} - \mu_{X_j}) + \varepsilon_i, 1 \leq i \leq K \quad (2.25)$$

where,

$$Q \leq K - 1 \quad (2.26)$$

Therefore, equation (2.21) is reformed into

$$\sigma_\varepsilon^2 = \frac{\sum_{i=1}^K \left(Y_i - \left(\hat{\mu}_Y + \sum_{j=1}^Q \hat{\beta}_j (x_j - \mu_{X_j}) \right) \right)^2}{K - Q - 1} \quad (2.27)$$

and s_{11} is the upper left hand entry in the matrix $(D^T D)^{-1}$ where D is of the form

$$D = \begin{bmatrix} 1 & X_{11} - \mu_{1X} & X_{21} - \mu_{2X} & \cdots & X_{Q1} - \mu_{QX} \\ 1 & X_{12} - \mu_{1X} & X_{21} - \mu_{2X} & \cdots & X_{Q1} - \mu_{QX} \\ 1 & X_{13} - \mu_{1X} & X_{21} - \mu_{2X} & \cdots & X_{Q1} - \mu_{QX} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & X_{1K} - \mu_{1X} & X_{21} - \mu_{2X} & \cdots & X_{Q1} - \mu_{QX} \end{bmatrix} \quad (2.28)$$

Then the 100(1- α)% confidence interval in equation (2.24) becomes

$$\hat{\mu}_Y \pm t_{K-Q-1, \left(1-\frac{\alpha}{2}\right)} \sqrt{\sigma_\varepsilon^2 s_{11}} \quad (2.29)$$

An important factor in the proper use of the CV technique is the selection of controls. In selecting potential controls, there are two things to look for. The first is an input of a random number or random variate. The input can be anything from a draw from a random distribution to a conditional switch. The second item of importance is that the expected value of the random input is known. There are many ways to determine what the expected value is, depending on the random input parameters. A table of expected values for distributions in THUNDER is presented in Appendix (B).

After all the potential candidates for controls are identified, the average of all the realizations of each potential candidate must be calculated and output in addition to the MOE of interest for each replication. Since the correlation between the control candidates and the MOE is unknown, a stepwise regression must be performed to identify which control candidates are significantly correlated to the selected MOE.

2.4.2. Common Random Numbers.

Common Random Numbers (CRN), also known as correlated sampling, is a relatively intuitive VRT. The rationale behind CRN is to induce a positive correlation in the random inputs between two or more configurations of a study. The positive correlation will diminish the noise generated by the difference in random inputs and in turn reduce the variance in the difference between the outputs. To create the positive correlation, the two configurations should use the same random variable inputs. The following theory behind CRN was adapted from Law and Kelton. (20:582-598)

To understand CRNs, consider two alternative configurations of a single simulation, where X_{1j} and X_{2j} are values from the first and second configuration on the j^{th} independent replication. Also consider, the estimate in question is equation (2.30).

$$\zeta = \mu_1 - \mu_2 = E[X_{1j}] - E[X_{2j}] \quad (2.30)$$

Let there be n replications of each system and let

$$Z_j = X_{1j} - X_{2j}, j = 1, 2, \dots, n \quad (2.31)$$

then

$$E[Z_j] = \zeta \quad (2.32)$$

Therefore, equation (2.33) is an unbiased estimator of ζ .

$$\bar{Z}(n) = \frac{1}{n} \sum_{j=1}^n Z_j \quad (2.33)$$

Since the Z_j 's are independent, identically distributed (IID) random variables,

$$\text{Var}(\bar{Z}(n)) = \frac{\text{Var}(Z_j)}{n} = \frac{\text{Var}(X_{1j}) + \text{Var}(X_{2j}) - 2\text{Cov}(X_{1j}, X_{2j})}{n} \quad (2.34)$$

If X_{1j} and X_{2j} are independent, then

$$\text{Cov}(X_{1j}, X_{2j}) = 0 \quad (2.35)$$

If then X_{1j} and X_{2j} are not independent and are positively correlated

$$\text{Cov}(X_{1j}, X_{2j}) > 0 \quad (2.36)$$

then $\text{Var}(\bar{Z}(n))$ will be reduced.

The key to the implementation of CRN is synchronization. The random number streams should match up between the two configurations as much as possible. This means, that a random number drawn should be used for the same purpose in both configurations. Ideally, all the random variate draws should be applied in exactly the same way for both configurations. To synchronize the simulations, some initial coding is involved. First, all of the points in the simulation where a random number or variate is drawn must be identified. Then, each point is then assigned its own random number stream.

A problem that may arise, when coding for CRN, is the sufficiency of the RNG. A primary concern should be how to keep track of all the different random number streams. Some large simulations like THUNDER could require hundreds of streams. Ideally, each of the streams should be independent and not overlap. This could be

difficult, because these simulations could have millions or even billions of random number draws. Therefore, a large RNG with built in functions that keep track of random number streams is beneficial.

2.4.3. Antithetic Variates.

Antithetic variate (AV) VRT is similar to CRN. As in CRN, correlation is induced between separate runs, but this time the object is to induce a negative correlation. The main difference is that instead of having two configurations of one system, there only needs to be one system. The following is an excerpt from Law and Kelton(20:598-604).

The basic idea is to make pairs of runs of a model where if the first run observes a “small” observation, then the second run observes a “large” observation. Therefore, the two observations are negatively correlated. To obtain the negative correlation, complementary numbers are used. For example, if U_k is a particular random number used for a particular purpose in the first run, then $1-U_k$ is used for the same particular purpose on the second run. The use of $1-U_k$ is valid, since $U \sim U(0,1)$ then $1-U \sim U(0,1)$ as well. Note that like CRN, synchronization is extremely important to the successful use of AV.

To understand the basis for AV, suppose there are n pairs of runs in a simulation resulting in observations $(X_1^{(1)}, X_1^{(2)}), \dots, (X_n^{(1)}, X_n^{(2)})$, where $X_j^{(1)}$ is from the normal run of the j^{th} pair, and $X_j^{(2)}$ is from the antithetic run of the j^{th} pair. Both $X_j^{(1)}$ and $X_j^{(2)}$ are legitimate observations of the simulation, therefore

$$E[X_j^{(1)}] = E[X_j^{(2)}] = \mu \quad (2.37)$$

Since each run is independent, each pair of runs is independent. Now let

$$X_j = \frac{(X_n^{(1)} + X_n^{(2)})}{2} \quad (2.38)$$

and let

$$\bar{X}(n) = \frac{1}{n} \sum_{j=1}^n X_j \quad (2.39)$$

be the unbiased point estimator of

$$\mu = E[X_j^{(1)}] = E[X_j] = E[\bar{X}(n)] \quad (2.40)$$

Since the X_j 's are IID,

$$\text{Var}[\bar{X}(n)] = \frac{\text{Var}[X_j]}{n} = \frac{\text{Var}[X_j^{(1)}] + \text{Var}[X_j^{(2)}] + 2\text{Cov}[X_j^{(1)}, X_j^{(2)}]}{4n} \quad (2.41)$$

If a negative correlation could be induced between $X_j^{(1)}$ and $X_j^{(2)}$, then

$$\text{Cov}[X_j^{(1)}, X_j^{(2)}] < 0 \quad (2.42)$$

which reduces $\text{Var}[\bar{X}(n)]$.

2.4.4. Control Variates and Antithetic Variates.

Kwon and Tew (15) compared three methods of combining Control Variates and Antithetic Variates. The first method consists of using CV on a simulation while using AV only on the random components not used in the CV technique. The second method consists of using CV on a simulation while using AV only on the random components used in the CV technique. The third method consists of using CV on a simulation while using AV on all of the random components in the simulation. Kwon and Tew concluded

that under general assumptions, the combined methods yield superior performance. They also found that the third method outperformed the other two. Method three is the method applied to THUNDER for this research.

The basic application behind method three of Kwon and Tew is to obtain the average response and the mean of the control variates across h pairs of replicates. The theory follows from Kwon and Tew (15). Four properties are derived.

1. Since the random inputs into the simulation are essentially independent, there is Homogeneity of response variances across replicates,

$$\text{Var}[y_i] = \sigma_y^2 \text{ for } i = 1, 2, \dots, 2h \quad (2.43)$$

2. Antithetic effect: there is homogeneity of response correlations across replicate pairs and independence of responses between replicate pairs.

$$\text{Cov}[y_i, y_k] = \begin{cases} -\rho\sigma_y^2 & \text{for } i = k + 1 (k = 1, 3, \dots, 2h - 1) \\ 0 & \text{otherwise} \end{cases} \quad (2.44)$$

Note: the correlation across replicate pairs is a negative correlation. Thus, ρ is positive.

3. Control Variate and Antithetic effect: there is homogeneity of response-control variates covariance across replicates, homogeneity of response-control variates covariance across replicate pairs, and independence of response-control variates on different replicate pairs.

$$\text{Cov}[y_i, c_k] = \begin{cases} \sigma_{yc} & \text{for } i = k = 1, 2, \dots, 2h \\ \sigma_{yc}^{(1)} & \text{for } i = k + 1 \text{ or } k = i + 1 (\min\{i, k\} = 1, 3, \dots, 2h - 1) \\ \mathbf{0}_{(s \times 1)} & \text{otherwise} \end{cases} \quad (2.45)$$

4. Antithetic effect also gives us homogeneity of control variates covariances across replicates, homogeneity of control variates covariances across replicate pairs, and independence of control variates on different pairs of replicates.

$$\text{Cov}[c_i, c_k] = \begin{cases} \Sigma_c & \text{for } i = k = 1, 2, \dots, 2h \\ \Sigma_c^1 & \text{for } i = k + 1 (k = 1, 3, \dots, 2h - 1) \\ 0_{(s \times s)} & \text{otherwise} \end{cases} \quad (2.46)$$

The following equations can be derived from the four properties above.

$$\text{Var}[\bar{y}_j] = \frac{1}{4} (\text{Var}[y_{2j-1}] + \text{Var}[y_{2j}] + 2\text{Cov}[y_{2j-1}, y_{2j}]) = \frac{1}{2} (1 - \rho) \sigma_y^2 \quad (2.47)$$

$$\text{Cov}[\bar{c}_j] = \frac{1}{4} (\text{Cov}[c_{2j-1}] + \text{Cov}[c_{2j}] + 2\text{Cov}[c_{2j-1}, c_{2j}]) = \frac{1}{2} (\Sigma_c + \Sigma_c^{(1)}) \quad (2.48)$$

and

$$\text{Cov}[\bar{y}_j, \bar{c}_j] = \frac{1}{4} \text{Cov}[y_{2j-1} + y_{2j}, c_{2j-1} + c_{2j}] = \frac{1}{2} (\sigma_{yc} + \sigma_{yc}^{(1)}) \quad (2.49)$$

for $j = 1, 2, \dots, h$. Under the joint normality assumption and properties from equations (2.43), (2.44), (2.45), and (2.46), the joint distribution of \bar{y}_j and \bar{c}_j is given as

$$\begin{bmatrix} \bar{y}_j \\ \bar{c}_j \end{bmatrix} \sim N_{s+1} \left(\begin{bmatrix} \mu_y \\ \mathbf{0}_{(s \times 1)} \end{bmatrix}, \frac{1}{2} \begin{bmatrix} (1 - \rho) \sigma_y^2 & (\sigma_{yc} + \sigma_{yc}^{(1)})^T \\ \sigma_{yc} + \sigma_{yc}^{(1)} & \Sigma_c + \Sigma_c^{(1)} \end{bmatrix} \right) \text{ for } j = 1, 2, \dots, h \quad (2.50)$$

Since \bar{c}_j ($j = 1, 2, \dots, h$) are independent, the unconditional variance for $\hat{\mu}_y$ is

$$\text{Var}[\hat{\mu}_y] = \frac{\tau^2}{2h} \left(\frac{h-2}{h-s-2} \right) \quad (2.51)$$

where

$$\tau^2 \equiv (1 - \rho) \sigma_y^2 - (\sigma_{yc} + \sigma_{yc}^{(1)})^T (\Sigma_c + \Sigma_c^{(1)})^{-1} (\sigma_{yc} + \sigma_{yc}^{(1)}) \quad (2.52)$$

Therefore, a reduction in variance of $\hat{\mu}_y$ will occur if the effects due to AV and CV together compensate for the loss factor given as $((h-2)/(h-s-2))$. Where s is the number of random number streams used to derive the control variate random numbers.

2.4.5. Control Variates and Common Random Numbers.

Yang and Nelson (44) developed a method that combines CVs and CRNs in applications of multiple comparisons. Multiple comparisons compare the expected values of univariate performance measures common to two or more systems by constructing simultaneous interval estimates of the differences in expected performance. Yang and Nelson address three types of multiple comparison procedures. They are Tukey's all-pairwise-multiple comparison (MCA) procedure, Hsu's multiple comparisons-with-the-best (MCB) procedure, and Dunnett's multiple-comparisons-with-a-control (MCC) procedure. MCA is used to determine the difference between the performance of each system design and every other system design. MCB is used to identify the system with the largest mean performance. MCC is used to determine the difference between the mean performance of a selected system design and every other system design. Their goal was to refine the three procedures, using the variance reduction techniques of CV and CRN, to increase sensitivity to differences in system performance.

The idea behind Yang and Nelson's approach is to use the following control variate estimators to estimate the mean performance for a system when applying multiple comparison procedures.

$$\hat{\theta}_i = \bar{Y}_i - \hat{\beta}_i (\bar{\mathbf{X}} - \boldsymbol{\mu}) \text{ for } i = 1, 2, \dots, r \quad (2.53)$$

where r is the total number of systems, \bar{Y}_i is the mean performance measure, $\hat{\beta}_i$ is the control variate estimates generated through least squares estimates, \mathbf{X} is a vector of independent random variables with known mean vector $\boldsymbol{\mu}$. An assumption required to do this is that the random variables \mathbf{X}_j , the control vectors, are available and identical across all systems. Therefore the control vectors must be available in each system design so they can be forced to take identical values through the application of CRN. The other random inputs into the system need to be independent to develop the control variate estimation.

Yang and Nelson modify the interval estimates for all three multiple comparison procedures to use the control variate estimation which relies on the fact that the control vectors are identical across all systems. They then develop the following theorem

$$\frac{E[H_{CV} | \mathbf{X}]}{E[H]} \xrightarrow{P} \sqrt{1 - R^2} \leq 1 \quad (2.54)$$

where $E[H_{CV} | \mathbf{X}]$ is the expected width of the standard control variate interval and $E[H]$ is the expected width of the multiple comparison interval. The equation calculates how the difference intervals developed by the control variates are smaller than the normally generated difference intervals.

2.4.6. Other Techniques.

There are many other VRTs than CV, CRN, and AV. In December of 1983, Lieutenant Colonel Mohamed Refat Elhefny (6) produced a thesis comparing many variance reduction techniques. He performed an extensive literature review to identify

and learn about the different VRTs. The following is a list of all the VRTs covered in LtCol Elhefny's research.

- Importance Sampling
- Russian Roulette and Splitting
- Systematic Sampling
- Stratified Sampling
- Expected Value
- Statistical Estimation
- Correlated Sampling
- History Reanalysis
- Control Variates
- Antithetic Variates
- Regression
- Sequential Sampling
- Orthogonal Functions
- Adjoint Method
- Transformation
- Conditional Monte Carlo

Within his research he created a table that outlines the characteristics of many VRTs.

The table has been reproduced in Appendix (H). The table includes a description, criteria for application, advantages, disadvantages, and typical applications for each technique.

LtC Elhefny concluded, "there is no single technique which is the most suitable technique for every simulation problem."(6:VI-1) He also thought that research should be performed to identify VRTs that may be affective for specific simulations. This could aid the analysis by identifying VRTs that may work with a simulation.

2.4.7. Previous Variance Reduction Studies.

There have been many studies in variance reduction techniques. Curtis Smith from the Naval Postgraduate School (NPS) set out to identify VRTs that are applicable to a class of stochastic combat simulations and then exhibit their performance in the applications. He applied the Antithetic Variates and Stratified Sampling techniques to a simple stochastic combat simulation. He proposed that both of these techniques are capable of variance reduction in stochastic combat models. Since the work was on a simple stochastic combat simulation, it was recommended that further studies on larger, real world simulations be performed. (31)

2.5. Random Number Generator

The random number generator (RNG) is an integral part of a stochastic simulation. Therefore, it should be of great interest to the analyst as to what RNG is used for a simulation and how well it performs. Currently, most programming software use small linear congruential generators (LCGs) as the random number generators. It is recognized by simulation experts that small LCGs, with moduli around 2^{31} , should not be used for most purposes. In fact, the period on most any LCG can be exhausted in a matter of minutes on a standard PC and LCGs are known to have poor point structure, both of which can bias simulation results. L'Ecuyer, proposed to replace the more common LCGs with a more robust RNG method called a combined multiple recursive generator (CMRG). L'Ecuyer, Simard, Chen, and Kelton have produced a CMRG RNG package, which is readily available on the Internet and is reviewed below. (18)

A parameter set for a CMRG, from a previous paper by L'Ecuyer, was selected as the backbone of the proposed RNG package. The parameter set is called MRG32k3a and was one of many sets that were discovered after a years worth of computer processing time (16). MRG32k3a has a long period of approximately 2^{191} or 3.1×10^{57} . RNGs with longer periods have been proposed, but MRG32k3a is more efficient with today's computers and the period is long enough not to be depleted by a years worth of computing. To remain efficient, a parameter set was chosen that had the ability to use floating-point arithmetic. Floating-point arithmetic is much faster to perform than regular arithmetic. MRG32k3a is also very sound statistically. The random number stream from MRG32k3a is so uniform; they pass the spectral test in at least 45 dimensions. This

means that when generating sets of t numbers, they would cover a t -dimensional unit hypercube very uniformly.

The implementation of MRG32k3a is relatively simple. It maintains only 2 components, each of order 3. The components are stored in vectors. At step n , the vectors would be as follows.

$$s_{1,n} = (x_{1,n}, x_{1,n+1}, x_{1,n+2}) \quad (2.55)$$

$$s_{2,n} = (x_{2,n}, x_{2,n+1}, x_{2,n+2}) \quad (2.56)$$

The vectors evolve according to the equation (2.57) and (2.58).

$$x_{1,n} = (1403580 \times x_{1,n-2} - 810728 \times x_{1,n-3}) \bmod 4294967087 \quad (2.57)$$

$$x_{2,n} = (527612 \times x_{1,n-1} - 1370589 \times x_{1,n-3}) \bmod 4294944443 \quad (2.58)$$

Then the output u_n is defined by the following relationship.

$$u_n = \begin{cases} z_n / 4294967088 & \text{if } z_n > 0 \\ 4294967087 / 4294967088 & \text{if } z_n = 0 \end{cases} \quad (2.59)$$

where

$$z_n = (x_{1,n} - x_{2,n}) \bmod 4294967087 \quad (2.60)$$

To create multiple streams, the full period needed to be broken into smaller sections that are equal in length. The goal was to find a size for the streams and substreams that are relatively long and have good statistical properties. In essence each stream and substream should resemble a stand alone random number generator. To do this, the statistical structure of many different streams and substreams all ranging in length, between 2^{51} and 2^{150} were examined. The combination of each stream consisting of 2^{127} numbers, with 2^{51} substreams consisting of 2^{76} numbers was chosen. Since the

streams and substreams are of equal length, four 3×3 matrices were developed so that the software could advance the state of the RNG by either 2^{127} or 2^{76} numbers with a single matrix multiplication. This allows the software to immediately jump to the next stream or substream.

To maintain the proper synchronization within the RNG, the computer keeps track of the beginning of the current stream, the beginning of the current substream, the beginning of the next substream, and the current state of the stream for each stream. This allows the user to reset the stream, reset the substream, jump to the next stream or jump to the next substream without losing continuity.

The speed of the MRG32k3a generator was compared with a commonly used LCG, `lcgrand` from Law and Kelton (16). A total of 10^9 random numbers were generated from both RNGs and were timed. The RNGs were run on a 600MHz PIII with 128MB of RAM, running Windows 98. MRG32k3a completed the run in 12.9 minutes while `lcgrand` completed the run in 14.8 minutes. Even though the MRG32k3a has more than twice as many calculations as a LCG, it still runs faster. Primarily, this is because the code for MRG32k3a implements floating-point arithmetic. To implement floating-point arithmetic, no variable or intermediate variable can exceed the precision of the computer it is running on, which is generally 32 bits. To make sure the calculations do not exceed the precision of the computer, the backbone equations have been slightly modified to store the intermediate calculation variables in smaller variables.

The RNG package includes many extra utilities to aid the use. First, the seed values for the whole package or individual stream can be changed. Second, each stream can be set to produce Antithetic variables for variance reduction. Third, the stream can

be reset to the start of the stream or substream. Finally, the precision of the uniform random number can be increased from 32-bit precision to 53-bit precision. A list of C routines is located in Appendix (G).

2.6. Major Shared Resource Center and Divide and Conquer

The ASC MSRC is a computational science facility. It supports various DoD research including development, test, and evaluation. As part of the DoD's High Performance Computing (HPC) Modernization Program, the ASC MSRC uses high performance computing research and visualization. To provide an interface between the analyst and HPC computing resources, the Divide and Conquer (D&C) system was developed. D&C has a web based Graphical User Interface (GUI) that allows an analyst to specify parameters for a study. D&C will take the study parameters and automatically set up all requested replications and directories. After setting up the replications, D&C queues the replication requests in the specified HPC resource.

2.7. Matlab and Regression

Matrix Laboratory (MATLAB®) is a high-performance language for technical computing. It was developed to provide easy access to matrix software, embedding state of the art software for matrix computation. The basic data element is an array that does not require dimensioning, giving the ability to solve many technical computing problems, specifically those with matrix and vector formulations, without the need to write a program in a scalar, noninteractive language such as C, Visual Basic, or Fortran.

MATLAB features a family of add-on application-specific solutions called toolboxes. Toolboxes are collections of MATLAB functions that extend the MATLAB environment to solve particular classes of problems. One of the MATLAB toolboxes is

the statistics toolbox (24). The statistics toolbox is a collection of statistical tools built on the MATLAB computing environment. The toolbox supports a wide range of common statistical tasks, from random number generation, to curve fitting, to design of experiments, statistical process control, and regression (25).

A useful function from the statistical toolbox is `stepwisefit`. The following information about `stepwisefit` was taken from the MATLAB statistics documentation. `Stepwisefit` uses stepwise regression to model the response variable y as a function of the predictor variables represented by the columns of the matrix X . A standard call to the `stepwisefit` function is `[b, se, pval, inmodel, stats, nextstep, history] = stepwisefit(X, y, 'Param1', value1, 'Param2', value2, ...)`. Where $X, y, 'Param1', value1, 'Param2', value2$, etc. are function parameters and $b, se, pval, inmodel, stats, nextstep$, and $history$ are function results. Table 2.1 contains a description of the `stepwisefit` parameters. b is a vector of estimated coefficient values for all columns of X . The b value for a column not included in the final model is the coefficient that you would obtain by adding that column to the model. se is a vector of standard errors for b . $pval$ is a vector of p-values for testing whether b is 0. $inmodel$ is a logical vector, whose length equals the number of columns in X , specifying which predictors are in the final model. A 1 in position j indicates that the j th predictor is in the final model; a 0 indicates that the corresponding predictor is not in the final model. $stats$ is a structure containing additional statistics. $nextstep$ is the recommended next step, either the index of the next predictor to move in or out, or 0 if no further steps are recommended. $history$ is a structure containing information about the history of steps

taken. The following table specifies one or more of the name/value pairs used as parameters (23).

Table 2.1: Parameter Specifications for Stepwisefit (23)

Parameter Name	Parameter Value
'inmodel'	Logical vector specifying the predictors to include in the initial fit. The default is a vector of all zeros, specifying no predictors.
'penter'	Maximum p-value for a predictor to be added. The default is 0.05.
'premove'	Minimum p-value for a predictor to be removed. The default is 0.10.
'display'	'on' displays information about each step. 'off' omits the information.
'maxiter'	Maximum number of steps to take (default is no maximum)
'keep'	Logical vector specifying the predictors to keep in their initial state. The default is a vector of all zeros, specifying no predictors.
'scale'	'on' scales each column of X by its standard deviation before fitting. 'off' does not scale (the default).

2.8. Analysis

The following subsections contain calculations used in the analysis presented in chapter 4. The first subsection describes how to generate a halfwidth and a confidence interval. The second subsection gives the calculations for determining the number of replications needed to achieve a specified halfwidth. The third subsection outlines the calculations used to determine a paired-t CI. The last subsection describes the Bonferroni inequality and how to calculate it.

2.8.1. Confidence Intervals.

Confidence intervals (CIs) are used to determine the $100(1-\alpha)\%$ bound on an estimated mean. The CI is based heavily on the variance of the mean estimate. The standard equation for a CI is below.

$$CI = \mu_x \pm \delta(n, \alpha) \quad (2.61)$$

where

$$\mu_X = \frac{1}{n} \sum_{i=1}^n X_i \quad (2.62)$$

and

$$\delta(n, \alpha) = t_{n-1, 1-\alpha/2} \sqrt{\frac{S^2(n)}{n}} \quad (2.63)$$

and n is the number of sample points, $S^2(n)$ is the variance of the sample points, and $t_{n-1, 1-\alpha/2}$ is the upper $1 - \alpha/2$ critical point for the t -distribution with $n - 1$ degrees of freedom. Equation (2.63) is called the halfwidth (20:511-513).

2.8.2. Determining the Number of Replications.

To calculate the estimated number of replications needed to achieve a specified halfwidth β , the following equation would be used.

$$n_a^*(\beta) = \min \left\{ i \geq n : t_{i-1, 1-\alpha/2} \sqrt{\frac{S^2(n)}{i}} \leq \beta \right\} \quad (2.64)$$

To use the above equation, it is assumed that $S^2(n)$ is constant for all n (20:512).

2.8.3. Paired-t Confidence Interval.

The paired-t CI is a method of comparing two systems on the basis of a performance measure. The paired-t CI calculates a CI about the difference between the performance measures. If the CI contains zero then the performance measures from both systems can be assumed equivalent.

Lets say there are n_1 replications of a performance measure of interest one X_{1j} where j ranges from 1 to n_1 and there are n_2 replications of a performance measure of interest one X_{2k} where k ranges from 1 to n_2 . If $n_1 = n_2 = n$ then we can define

$$Z_j = X_{1j} - X_{2j}, j = 1, 2, \dots, n \quad (2.65)$$

Since the X_{ij} are taken from replications, the Z_j 's are IID random variables and the estimator for expected value of Z is

$$\bar{Z}(n) = \frac{\sum_{j=1}^n Z_j}{n} \quad (2.66)$$

and the estimator for the variance is

$$\hat{\text{Var}}[\bar{Z}(n)] = \frac{\sum_{j=1}^n [Z_j - \bar{Z}(n)]^2}{n(n-1)} \quad (2.67)$$

Now, to form the $100(1 - \alpha)\%$ CI

$$\text{CI}[\bar{Z}(n)] = \bar{Z}(n) \pm t_{n-1, 1-\alpha/2} \sqrt{\hat{\text{Var}}[\bar{Z}(n)]} \quad (2.68)$$

Where the halfwidth is defined as

$$\delta(n, \alpha) = t_{n-1, 1-\alpha/2} \sqrt{\hat{\text{Var}}[\bar{Z}(n)]} \quad (2.69)$$

2.8.4. Bonferroni Inequality.

In most simulations, an analyst is interested in several simultaneous performance measures. Suppose that I_s is a $100(1 - \alpha)\%$ CI for the measure of performance μ_s where $s = 1, 2, \dots, k$. The probability that all k CIs simultaneously contain their respective true measures is

$$P(\mu_s \in I_s \forall s = 1, 2, \dots, k) \geq 1 - \sum_{s=1}^k \alpha_s \quad (2.70)$$

Whether or not the I_s 's are independent. This is known as the Bonferroni inequality.

Therefore, to maintain a simulation level of α , choose α_s 's such that

$$\alpha = \sum_{s=1}^k \alpha_s, s = 1, 2, \dots, k \quad (2.71)$$

Chapter 3 uses the basic understanding of the different tools and techniques developed in this chapter. It describes how the techniques are applied and which tools are used in the application.

3. Methodology

This chapter begins with the research objective. It then transitions into choice of THUNDER model databases and MOEs, describing how the MOEs are collected for analysis. Next, there is a description of how the VRTs are performed. Finally, it finishes with a discussion of how the analysis replications are run at the Major Shared Resource Center (MSRC) through the Divide and Conquer (DAC) web interface.

3.1. Research Objective

The objective of this research is to study the use of three variance reduction techniques on THUNDER. The three techniques are Control Variates, Common Random Numbers and Antithetic Variates. There are three basic steps to obtain the research objective. First, identify a set of MOEs that are commonly used by THUNDER users. This will guarantee that the results will be of some interest to the users. Second, modify the THUNDER source code to implement the three techniques. This consists of identifying areas where random variates are drawn, creating an output file of the mean value for the random inputs and implementing a new random number generator. Third, analyze the results from the variance reduction techniques to determine which, if any, are effective and if effective how efficient the technique is when applied to the model.

3.2. Model Selection for THUNDER Analysis

There are three notional model databases that are used as examples and come with THUNDER. They are called Databig, Datasmall, and ME. Most THUNDER model databases are classified due to the amount and the nature of the data in the model.

Therefore, one of the notional models was selected for the THUNDER analysis so that this research would remain unclassified. There is little documentation about any of the three example models, except that one of the three data sets is a European scenario, while the other two data sets are Middle Eastern scenarios. Since the THUNDER introductory course uses the ME, a Middle Eastern scenario, database (7), it was selected to be the representative scenario for this research. It is a 5-day scenario consisting of blue forces from Saudi Arabia and red forces from Iraq.

Running the standard package ME scenario is applicable for both CV and AV, since they both are single-model VRTs. On the other hand, the standard application of CRN requires at least two configurations or models to be compared. Therefore, a modification to the original ME configuration is needed. Because little is known about the scenario, a file that should have a significant effect on the outcome of the MOEs was chosen. That file selected was *squadron.dat*. It contains information pertaining to squadrons in the scenario. To modify it significantly, 204 F-111 aircrafts were taken from the Blue forces. This eliminated all of the F-111 from the scenario. No modifications were made to any other ME input files. A section of Appendix C of the THUNDER Analyst Manual (33), pertaining to the *squadron.dat* file is located in Appendix (I).

3.3. Measure of Effectiveness Selection

The MOEs for the ME scenario were selected after discussion with expert THUNDER users (32). Three types of MOEs that seem to interest the interviewed users are forward line of troops (FLOT) movement, sortie generation and aircraft attrition. These MOEs can be extracted from standard THUNDER reports. The two types of

reports needed are Ground Combat Cycle reports (CC) and the Air War reports (AW). The output data for the FLOT movement is located in the CC-4 (FLOT Movement) reports, the data for sorties generated is located in the AW-5 (Sortie Generation) reports and the data for aircraft attrition is located in the AW-3 (Aircraft Loss Summary) reports. All three reports are contained within a single output file named *reports.std*. A one-day sample of these reports is located in Appendix (A). A set of 21 specific MOEs was selected from the three reports. The following table identifies all MOEs, aggregation level, force, and the reports they are calculated from.

Table 3.1: Measure of Effectiveness Table

MOE	AGGREGATION	FORCE	REPORT
A-10 Losses per Sortie (LPS)	System Level	BLUE	AW-3
A-6 Losses per Sortie (LPS)	System Level	BLUE	AW-3
BLUE Flown per Planned Sortie (FPS)	Force Level	BLUE	AW-5
BLUE Losses per Sortie (LPS)	Force Level	BLUE	AW-3
BLUE Square Miles Gained (SMG)	Force Level	BLUE	CC-4
DHAHRAN Flown per Planned Sortie (FPS)	Base Level	BLUE	AW-5
F-111 Losses per Sortie (LPS)	System Level	BLUE	AW-3
F-15 Losses per Sortie (LPS)	System Level	BLUE	AW-3
FA-18 Flown per Planned Sortie total (FPS total)	Squadron Level	BLUE	AW-5
FA-18 Flown per Planned Sortie DCA (FPS DCA)	Squadron Level	BLUE	AW-5
MIG-23 Losses per Sortie (LPS)	System Level	RED	AW-3
MIG-29 Losses per Sortie (LPS)	System Level	RED	AW-3
MIRAGE Flown per Planned Sortie total (FPS total)	Squadron Level	RED	AW-5
MIRAGE Flown per Planned Sortie INT (FPS INT)	Squadron Level	RED	AW-5
MIRAGE Losses per Sortie (LPS)	System Level	RED	AW-3
MUDAYSIS Flown per Planned Sortie (FPS)	Base Level	RED	AW-5
RED Flown per Planned Sortie (FPS)	Force Level	RED	AW-5
RED Losses per Sortie (LPS)	Force Level	RED	AW-3
RIYADH Flown per Planned Sortie (FPS)	Base Level	BLUE	AW-5
SHAIBAH Flown per Planned Sortie (FPS)	Base Level	RED	AW-5

For this research, all of the selected MOEs were calculated. To calculate the Losses per Sortie (LPS) MOEs for the specific system, squadron, base or force, the total number of losses were divided by the total number of sorties. To calculate the Flown per Planned Sortie (FPS) MOEs for the specific system, squadron, base or force, the total

flown sorties were divided by the total planned sorties. The SMG was the only MOE that only needed to be summed over the total number of replication days.

3.4. Parsing THUNDER reports

The format for the reports in *reports.std* is good for a single printout, but it is not a good format for manipulating the data. *reports.std* is a text file. This means, that the format of the file is for a nice display, which is generally not conducive to data manipulation. In addition to the text format, report CC-4 is produced every 12-simulation hours, while AW-3 and AW-5 are reported every 24-simulation hours. Therefore, there are twice as many CC-4 reports as there are AW-3 or AW-5 reports. Fortunately, the reports are relatively uniform and can be manipulated with a parsing script. The following chart describes the flow of the parsing script.

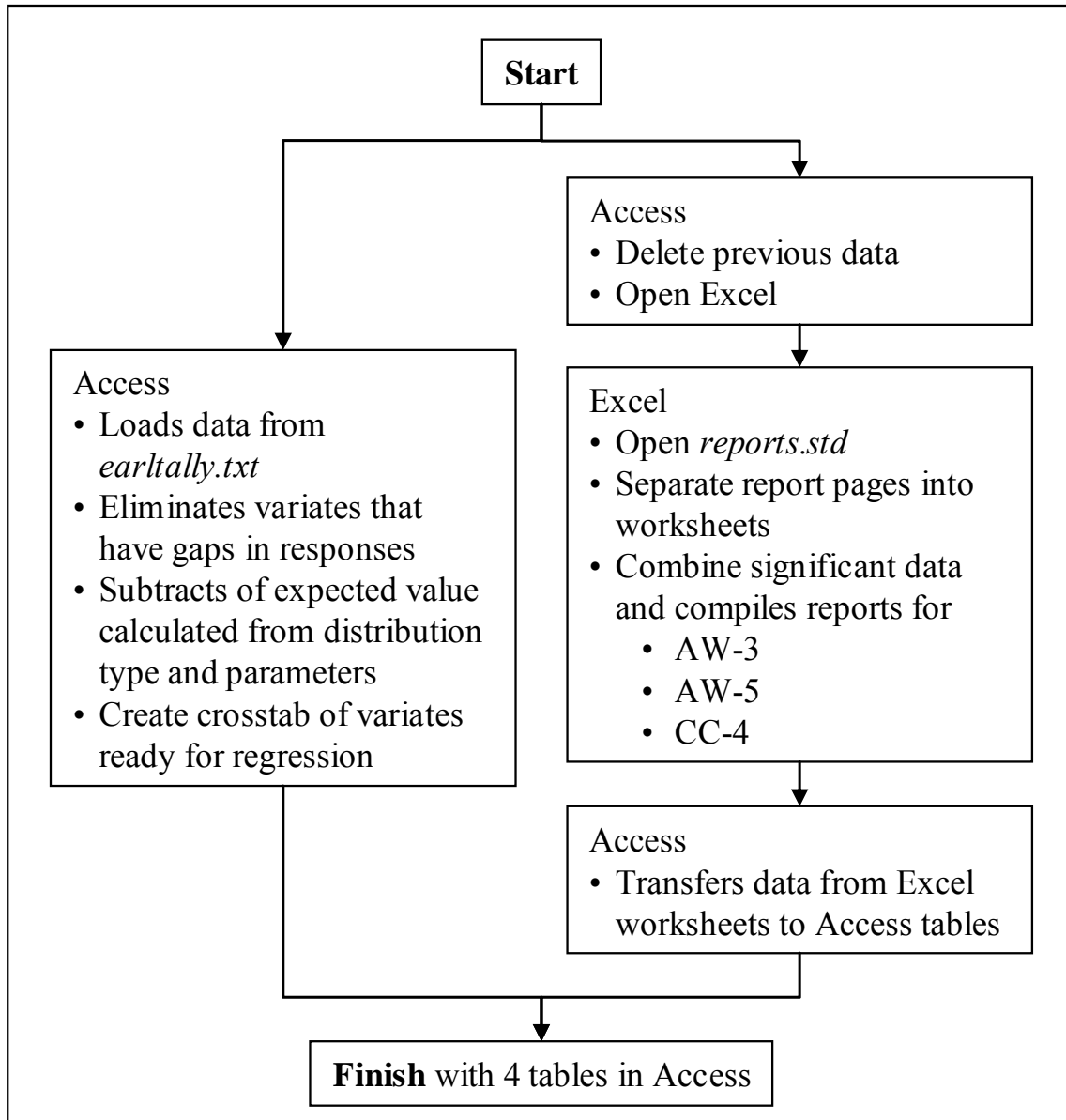


Figure 3.1: Parsing Script Flow Chart

Using a combination of Microsoft Excel, Microsoft Access and VBA, the *reports.std* is transformed from an ungainly text file into easy to manipulate Access tables. The tables produced are easily combined into a table that is readily transferable to software with regression capabilities such as JMP or MATLAB. THUNDER has been modified to produce a file named *earltally.txt* that contains the control variate

information and *earltime.txt* that contains the start and ending times for each replication.

A small example of the *earltally.txt* file is located below.

160,	7,	0.,	0.,	0,	-.00986138176387563802,	210
104,	11,	.1,	.33,	0,	45.43071582689116816311,	210
105,	11,	.1,	.33,	0,	43.01011811890460556639,	210
71,	9,	0.,	0.,	0,	601.25462303729726443179,	1179
47,	9,	0.,	0.,	0,	975.32737950515002722795,	1955
70,	9,	0.,	0.,	0,	258.31346595147626210575,	535
114,	9,	0.,	0.,	0,	4523.83226559217987983174,	9025

Figure 3.2: Example of earltally.txt File

The *earltally.txt* file is a comma separated text file. This means, that the file contains data separated into columns by commas. It has a total of 7 columns. The first column indicates which random variate the draw is from. The second column indicates what distribution the draw is from. Table 3.2 decodes all 13 of the distributions used by THUNDER. The third, fourth, and fifth columns are parameters 1, 2, and 3 respectively, of the distribution. The sixth column is the sum of the responses for the specific random variate draw. The final column is a count of the random variate draws.

Table 3.2: Random Distribution Decodes

code	decode
1	Beta
2	Binomial
3	Erlang
4	Exponential
5	Gamma
6	Logarithmic Normal
7	Normal
8	Poisson
9	Random
10	Triangle
11	Uniform
12	Weibull
13	Randi

The diagram in Figure 3.1 shows that the two output files, *earltally.txt* and *reports.std*, are handled separately and could be performed in parallel to speed up post

processing. Starting with the *earltally.txt* file, all replications are first loaded directly into Access. Then, Access singles out the random variates with only one entry per replication. Some random variates have distributions with parameters that change through out a THUNDER replication and therefore would have multiple entries in the *earltally.txt* file. Next, Access then filters out the random variates that were not used in all replications. Access then, calculates the expected value for each of the remaining data point and then subtracts the expected value from its corresponding data point. Finally, Access eliminates the resulting random variates that are zero or extremely close to zero. The final product is a table of random variates with deviations from the expected value that can be used as potential control variates. The table below has the random variates labeled across the top and identifies each replication as a row.

Table 3.3: Example of earltally.txt Final Product

REPLICATION	Total Of COUNT RESPONSE	__ADF105_1	__ADF121_1	__ADF121_2	__ADF121_3	__ADF140_3
1	125583	0.002579423	-0.000329738	-0.000770258	-0.000232268	0.004212851
2	132150	-0.009506824	-0.003220924	-8.88252E-05	0.00125997	0.003561292
3	133485	0.001791816	-0.001039787	-0.001135727	0.001023826	-0.002670896
4	125951	0.003829476	0.001651921	0.000130294	0.000752148	-0.003725937
5	133589	0.00681057	0.00051887	0.000205273	0.000267634	-0.001303033
6	122488	0.000387382	0.001067072	0.00013618	0.000565525	0.010540051
7	122536	-0.000581091	-0.000107913	-9.22039E-05	-0.001099367	-0.001221987
8	123779	0.003961604	-0.000126377	0.000277925	-0.000589475	0.000663163
9	134503	0.004555212	0.000114831	0.000903415	0.001249704	0.007879616

The file *reports.std* undertakes a more convoluted path. First Access deletes all of the old output tables and opens a template Excel file called *reportsifter.xls*. This Excel file contains macros and sheets designed to decode the three reports contained in *reports.std*. Then Excel opens up the *reports.std* file and separates each report page into its own Excel worksheet. After separating the report pages, Excel looks through each worksheet for report AW-3 and combines important data from AW-3 onto a new

worksheet. After all the AW-3 reports are found, Excel repeats the combining process for reports AW-5 and CC-4. It then saves the three combined worksheets into a new Excel workbook. Excel then repeats the entire process for each replication, until all of the *reports.std* files in the directory have been loaded and labeled with its corresponding replication. Finally, Access looks in the directory and transfers all three worksheets, AW-3, AW-5, and CC-4, from each of the new Excel workbooks into Access and combines them. A partial example of the AW-3 finished sheet is below.

Table 3.4: Example of AW-3 Final Product

REPLICATION	DAY	SIDE	ID	TYPE AIRCRAFT NAME	NUMBER OF SORTIES	LOSSES AIR TO AIR	LOSSES SURFACE TO AIR	LOSSES GROUND	LOSSES OTHER
1	4:0000	BLUE	1002	F-16	150	0	1	0	0
1	4:0000	BLUE	1099	ABL	22	0	1	0	0
1	4:0000	BLUE	1014	C-130H	4	0	0	0	0
1	4:0000	BLUE	1013	C-17	2	0	0	0	0
1	4:0000	BLUE	1012	KC-135	58	0	0	0	0
1	4:0000	BLUE	1011	E-8	4	0	0	0	0
1	4:0000	BLUE	1010	E-3	6	0	0	0	0
1	4:0000	BLUE	1009	F-14	108	1	0	0	0
1	4:0000	BLUE	1008	A-6	101	0	5	0	0
1	4:0000	BLUE	1007	F/A-18	48	0	0	0	0
1	4:0000	BLUE	1006	AV-8B	66	0	0	0	0
1	4:0000	BLUE	1005	F-15	296	0	0	0	0
1	3:0000	BLUE	1012	KC-135	55	0	0	0	0
1	4:0000	BLUE	1003	RF-4	44	1	1	0	0
1	4:0000	RED	2005	SU-25	50	5	3	0	0
1	4:0000	BLUE	1001	A-10	254	3	1	0	0
1	3:0000	RED	2099	SCUD	43	3	0	2	0
1	3:0000	RED	2006	MAINSTAY	3	0	0	0	0
1	3:0000	RED	2005	SU-25	61	5	10	0	0
1	3:0000	RED	2004	MIG-29	8	0	0	0	0
1	3:0000	RED	2003	MIG-21	96	13	0	0	0
1	3:0000	RED	2002	MIRAGE F-1	46	5	2	0	0
1	3:0000	RED	2001	MIG-23	61	11	8	0	0
1	3:0000	BLUE	1099	ABL	22	0	0	0	0
1	3:0000	BLUE	1014	C-130H	2	0	0	0	0

When the scripts are finished, the Access database contains four output tables. They are AW-3, AW-5, CC-4, and the potential control variates. Using Access, the report tables can be modified to obtain the selected MOEs. Then the selected MOEs can

be combined with the potential control variates to create regression ready tables. A copy of the scripts outlined above is available from the Center for Operations Analysis (COA) at AFIT. Also, a list of the modified files is located in Appendix (C).

3.5. Control Variates

The method of Control Variates relies on the output of a random variate where the expected value is known. In simulations, the random variates generated throughout a replication are effectively random and have a known expected value. Therefore, all the random variates generated in a simulation are potential control variates and should be identified and output from the simulation. When creating an output file of random variates, the variates should be labeled and produced with the label, type, parameters, and result. Therefore, the variates can be identified by the labels, the mean can be calculated from the result, and the expected value can be determined by the type and parameters.

In the late 1980's, a very limited version of the CRN technique was added to THUNDER. Reviewing this work, 245 of the 254 points where random variates are drawn were identified by following the nomenclature of CRN streams. The *control.dat* file, see Appendix (D), contains the list of random inputs and allows the user to assign random number streams to each of the random inputs. The nomenclature of the random input identifies which module the random input is from and also labels for more than one random input from a module. For example, **..AIR070.2** is a random input from module AIR070.SIM and it is the second random input from that module.

Since the random variate draws had been identified, the problem was, understanding how the variates are drawn, what they are used for, and how to output them. There are two methods used in THUNDER to draw a random variate. The first

method is where a random variate is drawn in a logical expression. An example is shown below.

```
'determine result of shot
IF .PK > 0.0
    AND RANDOM.F(RN.STREAM(..AIR070.2)) <= .PK
    LET .NUM.KILLED = 1
ELSE
    LET .NUM.KILLED = 0
ALWAYS
```

Figure 3.3: Logical Expression Example (Original)

The bolded section in Figure 3.3 is the random variate draw. The code **RANDOM.F()** is the SIMSCRIPT II.5 function for a uniform (0, 1) draw. **RN.STREAM** is a vector that contains the stream number for each random number draw. **..AIR070.2** is the label of the random variate draw. To capture the result, the random variate is drawn immediately prior to its use in THUNDER and placed in a variable called **EARL.RESPONSE**. Following the random number draw, the parameters are placed in variables **EB.P1**, **EB.P2**, and **EB.P3**. When a parameter is not used it is set to zero as in Figure 3.4. **EARL.RESPONSE** is then sent to an output routine **EARL.STORE**, along with the variate name, variate type, and all three parameters. **EARL.STORE** was specifically built to organize the random variate output for ease of use. Creating a single routine for all variate output allows for the ease of changing the output format if needed. After calling the output routine, THUNDER uses **EARL.RESPONSE** in place of the original random variate draw. Figure 3.4 is the modified version of logical expression in Figure 3.3. The added code to export the results is in bold.

```

''determine result of shot

*****
''*   Earl stuff       *
*****

EARL.RESPONSE = RANDOM.F(RN.STREAM(..AIR070.2))

EB.P1 = 0.0
EB.P2 = 0.0
EB.P3 = 0.0

CALL EARL.STORE
   GIVEN
       ..AIR070.2,
       ..RANDOM,
       EARL.RESPONSE,
       EB.P1,
       EB.P2,
       EB.P3

''* END STUFF

IF .PK > 0.0
   AND EARL.RESPONSE <= .PK
   LET .NUM.KILLED = 1
ELSE
   LET .NUM.KILLED = 0
ALWAYS

```

Figure 3.4: Logical Expression Example (Modified)

The second method to draw a random variate in THUNDER is through a subroutine. The subroutine is called because for the specific random variate, the user can set the variate distribution in an input file. Therefore the subroutine identifies the parameters and which distributions are needed and then draws from that distribution. The results from these random variate draws are returned from the subroutine and stored in a variable to be used by THUNDER. The example code in Figure 3.5 demonstrates a random variate subroutine call. The name of subroutine called is

UTL.720.CALCULATE.USER.FUNCTION. As in the first method, it has its own random variate identifier, which is **..AIR070.1**. The subroutine returns the value and places it in **.SHOT.DURATION.SEC**, which is then used in the lines following the subroutine call.

```
IF .DTBM.WPN.TYPE = ..AIRBORNE.LASER
OR .DTBM.WPN.TYPE = ..SPACE.BASED.LASER

CALL UTL.720.CALCULATE.USER.FUNCTION
GIVEN
    DWP.SHOT.DURATION.FN( .DWP ) ,
    RN.STREAM( ..AIR070.1 )
YIELDING
    .SHOT.DURATION.SEC

LET .SHOT.DURATION.SEC =
MAX.F( .SHOT.DURATION.SEC , 0.0 )
LET .TOTAL.ELAPSED.SECONDS
    = .DETECT.SECONDS.DELAY + .SHOT.DURATION.SEC
LET .INTERCEPT.FLAG = ..YES

ELSE
```

Figure 3.5: Random Variate Subroutine Call Example (Original)

To collect the results, code is added after the subroutine returns the random variate, but before it is used. The variate result, along with the variate name, type and parameters are sent to the same **EARL.STORE** as in the first method. Below is the modified version of Figure 3.5.

```

IF .DTBM.WPN.TYPE = ..AIRBORNE.LASER
OR .DTBM.WPN.TYPE = ..SPACE.BASED.LASER

CALL UTL.720.CALCULATE.USER.FUNCTION
  GIVEN
    DWP.SHOT.DURATION.FN(.DWP),
    RN.STREAM(..AIR070.1)
  YIELDING
    .SHOT.DURATION.SEC

*****
*** Earl stuff *
*****

EARL.RESPONSE = .SHOT.DURATION.SEC
EB.P1 = UF.PARM1(DWP.SHOT.DURATION.FN(.DWP))
EB.P2 = UF.PARM2(DWP.SHOT.DURATION.FN(.DWP))
EB.P3 = 0.0

CALL EARL.STORE
  GIVEN
    ..AIR070.1,
    UF.FUNCTION(DWP.SHOT.DURATION.FN(.DWP)),
    EARL.RESPONSE,
    EB.P1,
    EB.P2,
    EB.P3

*** END STUFF

LET .SHOT.DURATION.SEC =
MAX.F(.SHOT.DURATION.SEC, 0.0)
LET .TOTAL.ELAPSED.SECONDS
  = .DETECT.SECONDS.DELAY + .SHOT.DURATION.SEC
LET .INTERCEPT.FLAG = ..YES

ELSE

```

Figure 3.6: Random Variate Subroutine Call Example (Modified)

Note the code added to THUNDER is identified at the beginning of a section with **Earl stuff** and at an ending of a section with **END STUFF**. For a full comparison, Appendix

(E) and Appendix (F) contain the full unmodified and modified code respectively of Figure 3.3 through Figure 3.6.

A single five day run of the ME scenario in THUNDER can result in over 500,000 random variate draws. Outputting every random variate can create a very large output file. To save time and space, the random variates are stored as a table within THUNDER. Therefore, instead of storing the responses individually, the table keeps a running sum of the responses for repeated random variate draws and keeps track of the number of draws. THUNDER outputs this matrix in to the *earltally.txt* file upon completion of a replication. Figure 3.2 is an example of how the data is stored.

Using the script outlined above, *earltally.txt* can be combined with MOEs and displayed as a table that can be entered into a regression software package. Regression requires the amount of replications to equal or exceed the final number of control variates. Since there is a possibility of having 254 control variates, at least 254 replications should be performed to allow for the maximum number of control variates. Stepwise regression is preferred to single out the control variates that have statistically significant correlation with the selected MOE. There are many ways to perform a stepwise regression; the *stepwisefit* function in Matlab was used for this research. Three hundred replications of the scenario were used. Then a matrix of potential controls and MOEs were imported into a Matlab script. The matrix of potential controls contained the potential control variates left from the parsing script minus the known mean. Then *stepwisefit* with a parameter of max p-value to enter of 0.06 was used to identify the controls that are statistically significant to each MOE. After the controls were identified for each MOE, the MOEs are regressed with their corresponding controls and output into

an Excel workbook. A halfwidth for each MOE can be calculated with the known controls. This new halfwidth should be smaller than a halfwidth calculated from replications.

3.6. Common Random Numbers

As stated before, THUNDER had previously been coded for CRNs. The coding identifies the points where random numbers are drawn. Therefore, potential synchronization of the random number draws was already in place. Also, the *control.dat* file contains a method of assigning points where random variates are drawn from a specific random number stream. The problem with using CRNs with THUNDER is that the random number generator (RNG) only allows for 10 streams, while there are 254 random inputs where streams could be used. To solve this problem, a new random number generator was added to THUNDER. The random number generator proposed by Pierre L'Ecuyer (18) has 1.8×10^{19} streams, each of length 1.7×10^{38} elements. To put this in perspective, a standard software package RNG normally does not have streams and its entire length is generally between 1.6×10^7 and 2.8×10^{14} elements. As an added benefit, the random number generator is already coded in C with a support package. SIMSCRIPT II.5 will readily compile routines programmed in C and incorporates methods to call the compiled routines. Therefore, the proposed random number generation package could be compiled with THUNDER.

The current version of THUNDER tallies how many random number calls are made during a simulation run. It does this by rerouting a random number draw to a subroutine that increments a counter, draws a uniform [0, 1] random number, and returns the uniform [0, 1] random number. Therefore to direct THUNDER to use the new RNG

all that is needed to be done is replace the uniform [0, 1] random number draw from the standard function with a call to the new random number routines.

Not all random inputs are uniform [0, 1] random numbers. When THUNDER was coded to tally the number of random number draws, a series of subroutines were built to transform uniform [0, 1] random numbers into random variates from specified distributions with given parameters.

A new RNG designator has been placed in the *control.dat file*, Appendix (D), used to run a THUNDER replication. If this is set to YES, THUNDER will use the new RNG. When the new RNG is used, it reads a new seed file that contains the number of the first stream. If CRN designator in *control.dat* is also set to YES, THUNDER will then create a separate stream for each of the 254 points where random variates are drawn. At the end of a replication, THUNDER records the next starting seed in the seed file for each replication.

3.7. Antithetic Variates

Antithetic variates, like CRN, rely on synchronization. Since THUNDER has been setup with CRN, AV can utilize the synchronization. To implement AV, a replication of the simulation should be run normally with the new RNG and CRN in *control.dat* set to YES. Then a second replication of the simulation with the same streams should be run with the new RNG, CRN, and AV in *control.dat* set to YES. This will cause the simulation to be run with all the random numbers to be 1 – the random numbers of the previous replication. Then the two replications are averaged to obtain the variance reduction. This may seem tedious, but if all the random input are synchronized as in CRN, then a set of replications can be run normally and then followed by a set of

antithetic runs synchronized to the previous runs. Upon completion, the MOEs can be averaged.

The new RNG package compiled with THUNDER comes complete with the ability to use antithetic variates. The way this is implemented is by designating a stream as antithetic upon creation. The modified *control.dat* file has an antithetic designator. Setting the designator to YES, will assign all random number streams to antithetic. In addition, to perform AV effectively, the common random number designator should also be set to YES for both the normal and antithetic replications.

3.8. Integrated Control and Antithetic Variates

The third method outlined by Kwon and Tew (15) was used to analyze the variance reduction gained by integrating Control Variates and Antithetic Variates. Their method is relatively simple. First, run a simulation as you would for AVs with n replications, while producing the random variate output file. Then, combine each of the $n/2$ antithetic pairs and average them. This includes averaging both corresponding random variates and corresponding MOEs. The result is $n/2$ independent antithetic pairs. Then, use the antithetic pairs to perform a normal Control Variate analysis.

3.9. Integrated Control Variates and Common Random Numbers

To analyze the variance reduction by integrating Control Variates and Common Random Numbers a modification of the method employed by Yang and Nelson (44) was used because Yang and Nelson's multiple comparisons relies on identical control variates and THUNDER does not produce identical control variates, even with synchronization. The modified method is the application of the control variate estimators to develop

paired-t confidence intervals. First, independent THUNDER runs were performed using the base model database and the modified model database. These runs were used as a base paired-t confidence interval and to identify the random variates that are significantly correlated with the MOEs. These random variates were then synchronized while the rest were left independent for the analysis runs. Then, the control variate estimators identified in the base runs estimate the response and are used in the paired-t confidence intervals. The normal distribution is used instead of the studentized t distribution of calculating the halfwidth. This is because the studentized-t distribution resembles the normal distribution when the degrees of freedom become greater than 150.

3.10. Divide and Conquer and the Major Shared Resource Center

The first 2400 THUNDER replications were performed on the ASC MSRC HPC resources, while the last were performed on the AFIT Linux cluster. To perform the different types of analysis for this research, THUNDER needed to be run under several different settings. To organize and set up all of the replications with the different settings can be cumbersome. To make this practical, the ASC MSRC Divide and Conquer (DAC) web interface was used. The following diagram depicts the DAC process.

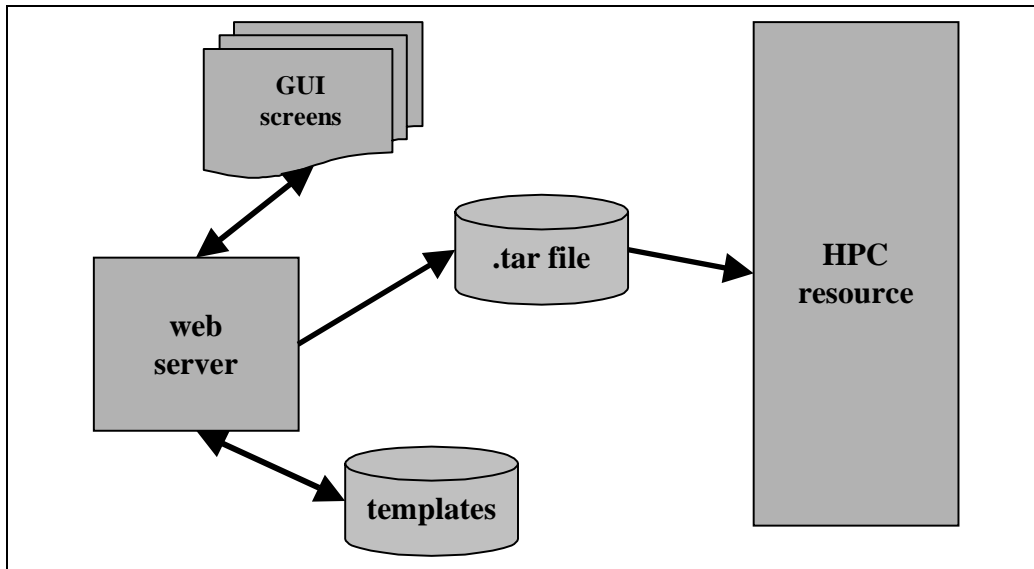


Figure 3.7: Divide and Conquer Flow Diagram (29)

The DAC has a graphical user interface (GUI) that loads a simulation template and allows the user to set up and modify select parameters for analysis. It even allows the user to select multiple levels of a parameter. After the parameters are set, the DAC web interface will automatically organize the runs and create scripts to perform the runs. These scripts are compressed into a .tar file and delivered to the proper HPC resource, unpacked and run.

3.11. Analysis

To analyze the data, the confidence interval halfwidths of the base case, no VRT, are compared with the confidence interval halfwidths generated by the variance reduction technique. Access databases were built to manipulate the data into the MOEs for each technique and then exported to Excel for ease of comparison. Then the variance reduction is calculated by dividing the difference between the base halfwidth and the VRT halfwidth by the base halfwidth.

A paired-t confidence interval is used, to determine if a pair of values is the same. This test determines the pair of values to be equal if the confidence interval includes zero. All statistical tests were calculated at the $\alpha = 0.05$ level.

Since there were three types of variance reduction techniques to analyze, different experiment settings were needed. A total of eight different run settings were identified for all of the experiments, with 300 replications at each setting for 2400 total THUNDER replications. The following table identifies the different setting used for the VRT analysis.

Table 3.5: Experiment Settings

	RNG	SYNCHRONIZED	ANTITHETIC	COLLECT CV	CONFIGURATION
SET	(NEW/OLD)	(YES/NO)	(YES/NO)	(YES/NO)	(ORIGINAL/MODIFIED)
A	OLD	NO	NO	YES	ORIGINAL
B	NEW	NO	NO	NO	ORIGINAL
C	NEW	NO	NO	YES	MODIFIED
D	NEW	YES	NO	YES	ORIGINAL
E	NEW	YES	NO	YES	MODIFIED
F	NEW	YES	YES	YES	ORIGINAL
G	OLD	NO	NO	NO	ORIGINAL
H	NEW	YES	NO	NO	ORIGINAL
M	NEW	NO*	NO	YES	ORIGINAL
O	NEW	NO*	NO	YES	MODIFIED
S	NEW	YES*	NO	YES	ORIGINAL
T	NEW	YES*	NO	YES	MODIFIED

RNG identifies use of the current (**OLD**) or MRG32k3a (**NEW**) random number generator. **SYNCHRONIZED** indicates whether all of the random inputs are synchronized or not. The values of (**YES***) indicates that only some of the random variates are synchronized and the values (**NO***) indicates a different stream than 1 was used to generate the independent random variates. **ANTITHETIC** identifies if the random number draws are drawn normally (**NO**) or using 1-*U* (**YES**). **COLLECT CV** identifies whether the replications output a controls file. **CONFIGURATION** indicates

the use of the standard ME model database (**ORIGINAL**) or the use of the ME model database with the 209 F-111's eliminated (**MODIFIED**).

4. Analysis

This section contains results and examples of analysis performed to determine the effectiveness of the variance reduction techniques applied to THUNDER. The first three sections cover the results from applying the control variate technique, common random numbers, and antithetic variates respectively. The fourth section details the combination of both control variates and antithetic variates. The fifth sections reports on the combination of control variates with common random numbers. The last section covers the comparison between the new random number generator and the original random number generator.

4.1. Control Variates

A total of 600 replications of the ME scenario were performed to analyze the effectiveness of the control variate technique. Table 4.1 details the experiment settings; remember that each set consists of 300 replications. All of the replications used the original random number generator, with no common random numbers, with no antithetic variates and used the original configuration of the ME scenario. The first 300 replications, set A, generated control variate information. They were used to determine the halfwidth for each MOE with and without control variates. The second 300 replications, set G, were generated without control variates. They were used, in conjunction with the set A, for comparing the difference in speed between generating control variates and not generating control variates.

Table 4.1: Control Variate Experiment Settings

	RNG	SYNCHRONIZED	ANTITHETIC	COLLECT CV	CONFIGURATION
SET	(NEW/OLD)	(YES/NO)	(YES/NO)	(YES/NO)	(ORIGINAL/MODIFIED)
A	OLD	NO	NO	YES	ORIGINAL
G	OLD	NO	NO	NO	ORIGINAL

The following analysis compares the halfwidths generated by standard replication and control variates. The second subsection estimates the number of extra replications needed to achieve a similar reduction as the reduction achieved through control variates. The following subsection demonstrates how control variates may be used in gaining insight into the workings of the simulation. The last subsection provides an analysis of the simulation speed, comparing time needed to produce a control variate output file and the time needed to run a simulation without producing a control variate file.

4.1.1. Replications vs. Variance Reduction Technique.

The ME scenario was replicated 300 times, generating the control variate file and in turn, creating a potential control variate table. The control variate table, along with the response table was processed through the control variate script to produce the control variate halfwidths. Then the halfwidths for each MOE were calculated at the $\alpha = 0.05$ level and compared to the control variate halfwidths. The results are below.

Table 4.2: Control Variate Halfwidth Reduction

MOE	REPLICATION		CONTROL VARIATE		PERCENT CHANGE
	MEAN	HALFWIDTH	MEAN	HALFWIDTH	
A-10 LPS	0.004928615	0.000271598	0.004947585	0.000270219	-0.51%
A-6 LPS	0.018843645	0.001023321	0.018829341	0.001014611	-0.85%
BLUE FPS	0.581540025	0.002144585	0.581287551	0.002034784	-5.12%
BLUE LPS	0.010229418	0.00015922	0.010225498	0.000157836	-0.87%
BLUE SMG	34487.47	81.58752506	34501.15753	79.42601286	-2.65%
DHAHRAN FPS	0.374067144	0.007240438	0.373871063	0.007070694	-2.34%
F-111 LPS	0.017016367	0.000422881	0.016995175	0.00041728	-1.32%
F-15 LPS	0.00642758	0.000296031	0.006433521	0.000293957	-0.70%
FA-18 FPS total	0.232338281	0.003721562	0.232495993	0.003661179	-1.62%
FA-18 FPS DCA	0.043787767	0.001197699	0.043683747	0.001181571	-1.35%
MIG-23 LPS	0.253296028	0.006221384	0.252744641	0.00619634	-0.40%
MIG-29 LPS	0.195555155	0.007370947	0.19570513	0.007264416	-1.45%
MIRAGE FPS total	0.598071397	0.004573737	0.598463965	0.004517323	-1.23%
MIRAGE FPS INT	0.702633484	0.005673337	0.703846015	0.005482963	-3.36%
MIRAGE LPS	0.274969404	0.00452846	0.275087315	0.004501166	-0.60%
MUDAYSIS FPS	0.19221417	0.005066926	0.192327882	0.004982654	-1.66%
RED FPS	0.391637103	0.001710069	0.39176041	0.001693386	-0.98%
RED LPS	0.192105922	0.001578977	0.19217664	0.001531504	-3.01%
RIYADH FPS	0.855569083	0.001545936	0.855668121	0.001516207	-1.92%
SHAIBAH FPS	0.499191886	0.006482834	0.499297882	0.006409984	-1.12%

A reduction in all the halfwidths is realized. The reduction may be small, but this is expected because as we can see in Table 4.3, R^2 from each model is also small.

Table 4.3: Control Variate RSquared

MOE	RSQUARED	ADJUSTED RSQUARED
A-10 LPS	0.017990681	0.017990681
A-6 LPS	0.026694585	0.02342846
BLUE FPS	0.12506954	0.11018977
BLUE LPS	0.021109417	0.021109417
BLUE SMG	0.100168792	0.081742215
DHAHRAN FPS	0.059778386	0.053446928
F-111 LPS	0.040550054	0.034089112
F-15 LPS	0.024657888	0.021384928
FA-18 FPS total	0.046169914	0.039746816
FA-18 FPS DCA	0.038015219	0.034787082
MIG-23 LPS	0.025816687	0.022547616
MIG-29 LPS	0.060690505	0.051170476
MIRAGE FPS total	0.044797447	0.038365106
MIRAGE FPS INT	0.095539229	0.083275355
MIRAGE LPS	0.016059425	0.016059425
MUDAYSIS FPS	0.052473379	0.046092729
RED FPS	0.026028565	0.026028565
RED LPS	0.06941087	0.063144276
RIYADH FPS	0.066740758	0.05728205
SHAIBAH FPS	0.029355585	0.026098389

A graphical example of the variance reduction can be seen in the following examples. They are the largest reduction, BLUE Flown per Planned Sortie, and the smallest reduction, MIG-23 Losses per Sortie.

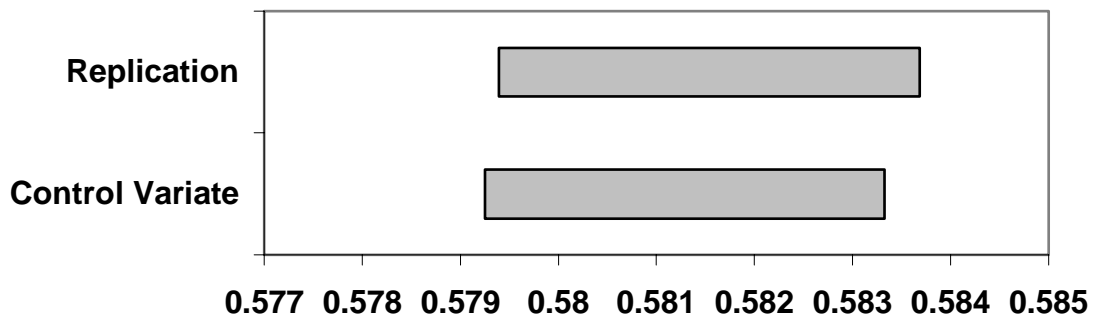


Figure 4.1: BLUE Flown per Planned Sortie Confidence Intervals

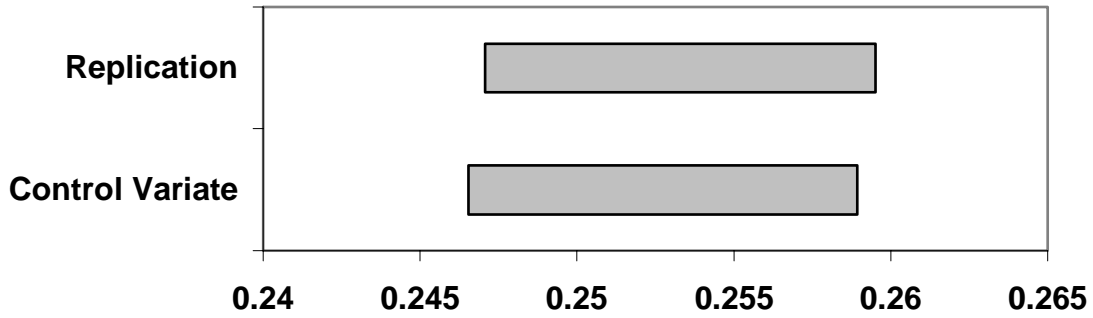


Figure 4.2: MIG-23 Losses per Sortie Confidence Intervals

There is a shift in the means between the replication and control variates. This is because the calculations for the replication mean is calculated by using the arithmetic average and the CV mean is calculated from regression using least squares estimates. Using the means from Table 4.2, the following table was generated and the absolute percent change was calculated.

Table 4.4: Absolute Percent Change In Means

MOE	REPLICATION MEAN	CV MEAN	PERCENT CHANGE
A-10 LPS	0.004928615	0.004947585	0.38%
A-6 LPS	0.018843645	0.018829341	0.08%
BLUE FPS	0.581540025	0.581287551	0.04%
BLUE LPS	0.010229418	0.010225498	0.04%
BLUE SMG	34487.47	34501.15753	0.04%
DHAHRAN FPS	0.374067144	0.373871063	0.05%
F-111 LPS	0.017016367	0.016995175	0.12%
F-15 LPS	0.00642758	0.006433521	0.09%
FA-18 FPS total	0.232338281	0.232495993	0.07%
FA-18 FPS DCA	0.043787767	0.043683747	0.24%
MIG-23 LPS	0.253296028	0.252744641	0.22%
MIG-29 LPS	0.195555155	0.19570513	0.08%
MIRAGE FPS total	0.598071397	0.598463965	0.07%
MIRAGE FPS INT	0.702633484	0.703846015	0.17%
MIRAGE LPS	0.274969404	0.275087315	0.04%
MUDAYSIS FPS	0.19221417	0.192327882	0.06%
RED FPS	0.391637103	0.39176041	0.03%
RED LPS	0.192105922	0.19217664	0.04%
RIYADH FPS	0.855569083	0.855668121	0.01%
SHAIBAH FPS	0.499191886	0.499297882	0.02%

As can be seen above, all of the absolute percent changes in means are positive, therefore the shift in means is relatively insignificant.

4.1.2. Variance Reduction Technique to Number of Replications.

Another way of looking at the reduction gained by using control variates is to calculate the number of replications needed to achieve the control variate halfwidth. To do this, the halfwidth calculation is iterated by incrementing the number of replications in the equation until the halfwidth is smaller than the control variate halfwidth. A major assumption to this method is the variance remains constant. The following table displays the number of replications needed to achieve the variance reduction.

Table 4.5: Number of Replications Required to Achieve Control Variate Reduction

MOE	REPLICATIONS	CHANGE IN REPLICATIONS	PERCENT CHANGE
A-10 LPS	304	4	1.33%
A-6 LPS	306	6	2.00%
BLUE FPS	333	33	11.00%
BLUE LPS	306	6	2.00%
BLUE SMG	317	17	5.67%
DHAHRAN FPS	315	15	5.00%
F-111 LPS	309	9	3.00%
F-15 LPS	305	5	1.67%
FA-18 FPS total	310	10	3.33%
FA-18 FPS DCA	309	9	3.00%
MIG-23 LPS	303	3	1.00%
MIG-29 LPS	309	9	3.00%
MIRAGE FPS total	308	8	2.67%
MIRAGE FPS INT	321	21	7.00%
MIRAGE LPS	304	4	1.33%
MUDAYSIS FPS	311	11	3.67%
RED FPS	306	6	2.00%
RED LPS	319	19	6.33%
RIYADH FPS	312	12	4.00%
SHAIBAH FPS	307	7	2.33%

4.1.3. Control Variate Insight.

The method of control variates has an added benefit to the analyst. It generates a series of random inputs that are statistically significant in their correlation to the selected MOE. Knowledge about these random inputs can give insight into how the simulation works. First, knowing the weight and sign of the coefficient can inform the analyst how much and in which direction a shift in the control can alter the selected MOE. The following table identifies the significant controls for each MOE and gives the weight and sign of the corresponding control.

Table 4.6: Control Variate Statistically Significant Controls

MOE	WEIGHT	CONTROL	MOE	WEIGHT	CONTROL
A-10 LPS	-0.0002	AIR060_2	MIG-23 LPS	-6.6526	ADF121_2
A-6 LPS	-0.0071	AIR050_2	MIG-29 LPS	0.1433	AIR101_1
	-0.0759	ISR000_4		0.6471	AIR528_1
BLUE FPS	-0.0722	AIR050_1	MIRAGE FPS total	-1.4314	BSE050_1
	-0.0659	AIR070_2		-0.2311	GRD095_1
	-0.0035	AIR800_3		-0.7147	ISR000_4
	0.3282	BSE400_1	-0.3242	ADF150_1	
	46.8237	PLA443_1	0.5198	AIR561_1	
	0.6659	UTL104_1	0.0855	AIR602_1	
BLUE LPS	0.0101	ADF150_2	MIRAGE FPS INT	-3.3544	ADF121_1
BLUE SMG	-23825.1823	ADF105_1	MIRAGE LPS	7.9362	ADF121_2
	40.5388	AIR060_2		0.0101	AIR800_3
	3649.5981	AIR101_2		-1.0679	BSE003_2
	-1408.6753	AIR561_2		106.4336	PLA443_1
	-20765.0668	AIR840_1	MUDAYSIS FPS	-0.2438	ADF150_2
	-27766.1967	AIR840_2	MIRAGE FPS INT	-0.0089	AIR800_3
-8446.2005	BSE400_1	0.1621		GRD095_2	
DHAHRAN FPS	-0.1779	AIR050_1	RED FPS	0.6949	BSE200_5
	-0.2230	AIR070_2	RED LPS	0.0922	ADF150_1
	0.9677	BSE400_1		-0.0629	AIR070_2
F-111 LPS	0.0213	ADF150_2		0.6117	UTL104_1
F-15 LPS	-0.0120	AIR060_1	RIYADH FPS	-0.2501	AIR007_1
	-0.1221	BSE200_5		-0.0395	AIR101_1
FA-18 FPS total	0.0069	AIR050_1		-0.0621	AIR101_2
	0.0019	AIR050_2	-0.0505	GRD095_1	
FA-18 FPS DCA	0.0252	AIR050_2	SHAIBAH FPS	-0.1675	AIR101_1
	-0.0889	AIR070_2		1.3115	BSE003_1
	-1.3057	AIR810_2			
	1.4195	ADF121_3			
	0.0006	AIR060_2			

The table above can also be used in conjunction with knowledge of the simulation code. If the analyst looks at how the controls are used, he may be able to identify systems or actions that affect the MOE. For example, take MOE BLUE SMG (Square Miles Gained). The controls ADF105_1, AIR060_2, AIR101_2, AIR561_2, AIR840_1, AIR840_2, and BSE400_1 are all significant. By looking at the code, the use of each of the random variates can be identified by examination of the module purpose, the

comments in the code and the nomenclature of the interacting variables. The following table outlines information gleaned from the code.

Table 4.7: Control Variate Purpose of Statistically Significant Controls

CONTROL	WEIGHT	MODULE PURPOSE	SPECIFIC DRAW PURPOSE
ADF105_1	-23825.18	Used to calculate the flight groups position, altitude, speed, average location, and delivery profile.	Used to check for point on battlefield. (Distribution)
AIR060_2	40.54	Manages defensive anti tactical ballistic missile mission detections and engagements.	Used in setting saturation delay on shooter. (Distribution)
AIR101_2	3649.60	Sets up and air engagement by creating and air-to-air engagement for each flight to be used for storing computations.	Used in determining the engagement probability. (.prob.engage < U(0,1))
AIR561_2	-1408.68	Determines if, having arrived at the target's estimated coordinate, the flight group can find the target.	Determines the success of a mid-course update. (U(0,1)<=.best.prob)
AIR840_1	-20765.07	Determines the number of target elements that are destroyed when a given weapons area of effect fully or partially covers a target.	Determine whether a live target element is hit. (U(0,1)<.prob.hit.live)
AIR840_2	-27766.20	Determines the number of target elements that are destroyed when a given weapons area of effect fully or partially covers a target.	Determine whether a live target element is hit. (U(0,1)<.exp.live.hits)
BSE400_1	-8446.20	Determine s the availability of aircraft, establishes the munition configurations, allocates fuels and determines whether to cancel or run the mission as scheduled.	Determines the cancellation of a sortie due to degrade. (U(0,1)<eawp.sortie.degrade)

Using the chart above, a number of system characteristics can be determined. First, by increasing in the saturation delay on the shooter, there will be a small increase in BLUE SMG. Second, it can be determined that increasing the number of random draws greater than the engagement probability will greatly increase the BLUE SMG. Another way to look at this is decreasing the air-to-air engagements will increase the BLUE SMG. Third, by increasing the success of a mid-course update will increase the BLUE SMG. Fourth, increasing the probability of hitting a live target will greatly increase the BLUE

SMG. Fifth, the greatest increase in BLUE SMG is related to the number of sorties. If the degrade in the sorties are large, then the number of sorties are reduced and the BLUE SMG is also reduced. An overall look at this implies that the more sorties that are generated and the fewer enemy engagements along with better strikes will lead to a more BLUE Square Miles Gained. This same analysis can be applied to the control variates related to other MOEs.

4.1.4. Replication Speed With And Without Generating Control Variates.

To test the difference in running times, the start and completion times for each replication is recorded and the difference is calculated in seconds. Then a paired-t CI is calculated and if the CI contains zero, it is determined that the times are not statistically different. The 300 replications performed while producing control variate information, set A, are compared to the 300 replications performed while not producing control variate information, set G, by subtracting the replication times of set G from set A. The confidence interval on the difference is (0.01284, 0.18049). A graphical representation is below.

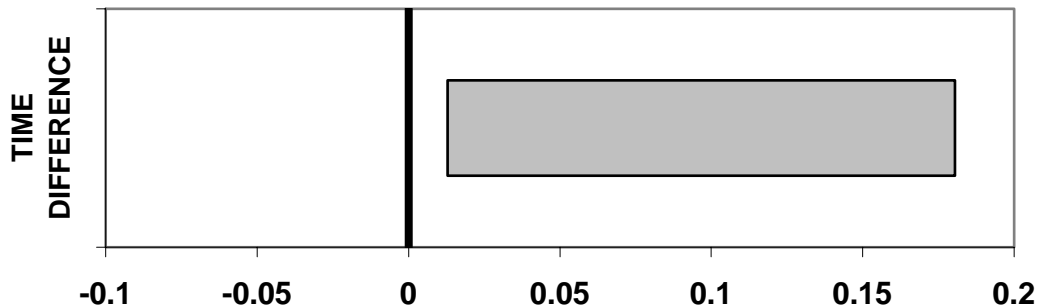


Figure 4.3: Replication Completion Difference Confidence Interval

Since the confidence interval does not contain zero, the completion times are statistically different at the $\alpha = 0.05$ level. Since the times for replications not generating the control

variates are subtracted from the times for replications generating the control variates, the CI implies that the times for generating the control variates are larger.

4.2. Common Random Numbers

To analyze the effectiveness of the CRN technique, a total of 1200 replications were performed. Table 4.8 details the experiment settings; remember that each set consists of 300 replications. The sets can be separated into two groups. The first group is the standard non-synchronized data that makes up the base data and the second group is the synchronized data. All replications were of the standard ME scenario, using the new RNG. The first 300 replications, set B, contained no changes to the database and with all random inputs using a single stream for each replication. The second 300 replications, set C, were performed with all of the F-111s removed from the database and with all random inputs using the same single streams applied to set B. The third 300 replications, set D, contained no changes to the database and were performed with all of the random inputs synchronized therefore, receiving their own random number stream in each replication. The last 300 replications, set E, were performed with all of the F-111s removed from the database and with the random inputs synchronized with set D.

Table 4.8: Common Random Number Experiment Settings

	RNG	SYNCHRONIZED	ANTITHETIC	COLLECT CV	CONFIGURATION
SET	(NEW/OLD)	(YES/NO)	(YES/NO)	(YES/NO)	(ORIGINAL/MODIFIED)
B	NEW	NO	NO	NO	ORIGINAL
C	NEW	NO	NO	YES	MODIFIED
D	NEW	YES	NO	YES	ORIGINAL
E	NEW	YES	NO	YES	MODIFIED

The following analysis compares the halfwidths generated by calculating the difference between scenario configurations. The first comparison is by the standard

method, not synchronized, and the second comparison is by CRN with synchronization. The second section highlights insights gleaned from using CRN.

4.2.1. Normal to Variance Reduction Technique.

The paired-t CI at the $\alpha = 0.05$ level was used to determine whether the MOEs generated from a configuration change in the ME scenario resulted in statistically different values. Then the paired-t halfwidths were compared to determine the reduction in variance. The following table displays the results of this comparison.

Table 4.9: Common Random Number Halfwidth Reduction

MOE	BASE		CRN		PERCENT CHANGE
	MEAN	HALFWIDTH	MEAN	HALFWIDTH	
A-10 LPS	-0.004978203	0.00053875	-0.005019134	0.000533584	-0.96%
A-6 LPS	-0.003968323	0.001541612	-0.003959031	0.001382776	-10.30%
BLUE FPS	0.07850412	0.00280076	0.079916562	0.002443302	-12.76%
BLUE LPS	-0.000834882	0.000253594	-0.00110882	0.000234114	-7.68%
BLUE SMG	323.05	109.3136609	265.22	115.3944755	5.56%
DHAHRAN FPS	0.047589307	0.008795164	0.046170201	0.007928092	-9.86%
F-15 LPS	-0.000518151	0.000438013	-0.000617566	0.000422892	-3.45%
FA-18 FPS total	0.023195554	0.004674708	0.023448124	0.004512142	-3.48%
FA-18 FPS DCA	0.000753974	0.001907906	-0.000751392	0.001799667	-5.67%
MIG-23 LPS	0.010507245	0.010701722	0.016051307	0.008963076	-16.25%
MIG-29 LPS	0.052738368	0.00954175	0.0621385	0.010117406	6.03%
MIRAGE FPS total	0.01092006	0.006458806	0.008898713	0.005904645	-8.58%
MIRAGE FPS INT	-0.002057046	0.007664981	-0.002582203	0.007259603	-5.29%
MIRAGE LPS	-0.001408885	0.006220598	0.005438013	0.005672349	-8.81%
MUDAYSIS FPS	0.073151537	0.005964334	0.067373498	0.005894866	-1.16%
RED FPS	0.034304208	0.002341687	0.032198334	0.002392857	2.19%
RED LPS	0.02384662	0.002443123	0.023647381	0.002339682	-4.23%
RIYADH FPS	-0.072238335	0.001832508	-0.071748036	0.001917861	4.66%
SHAIBAH FPS	0.090617611	0.009656621	0.089769928	0.010008527	3.64%

Looking above, we can see that the halfwidth is not always smaller. The changes highlighted above are the halfwidths that are reduced. This implies that there is not always a reduction in the variance when using CRN. The following two charts are a graphical representation of the largest reduction, MIG-23 LPS and the largest increase, MIG-29 LPS.

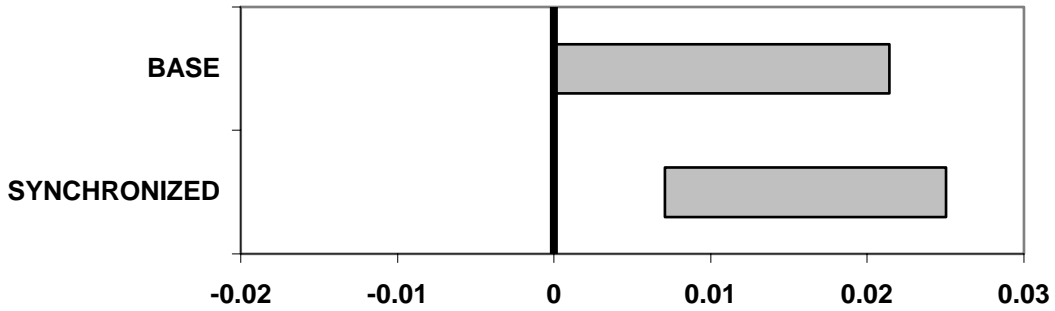


Figure 4.4: MIG-23 Losses per Sortie Value Difference Confidence Intervals

The confidence interval generated for the base (-0.00019,0.021209) and for the synchronized (0.007088,0.025014).

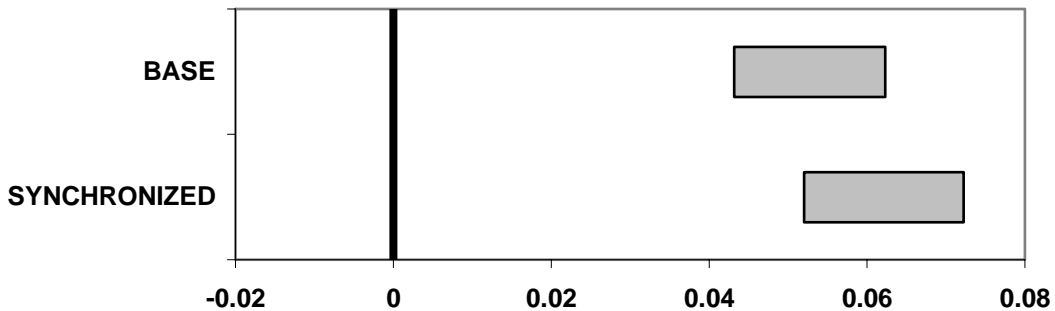


Figure 4.5: MIG-29 Losses per Sortie Value Difference Confidence Intervals

The confidence interval generated for the base (0.043197,0.06228) and for the synchronized (0.052021,0.072256).

4.2.2. Common Random Numbers Insights.

As can be seen above in Figure 4.4, the decision of whether the MOE results between configuration are statistically different or not, may change between the base non-synchronized and the synchronized, as a result from both the change in halfwidth and a shift in the mean value. The following table displays the decision results among the MOEs and identifies any changes in the decisions between the base and synchronized

results. Each of the CIs developed for the MOEs below are calculated at the $\alpha = 0.05$ level and are calculated separately.

Table 4.10: Common Random Number Configuration Decision

MOE	BASE DECISION	CRN DECISION
A-10 LPS	DIFFERENT	DIFFERENT
A-6 LPS	DIFFERENT	DIFFERENT
BLUE FPS	DIFFERENT	DIFFERENT
BLUE LPS	DIFFERENT	DIFFERENT
BLUE SMG	DIFFERENT	DIFFERENT
DHAHRAN FPS	DIFFERENT	DIFFERENT
F-15 LPS	DIFFERENT	DIFFERENT
FA-18 FPS total	DIFFERENT	DIFFERENT
FA-18 FPS DCA	NOT DIFFERENT	NOT DIFFERENT
MIG-23 LPS	NOT DIFFERENT	DIFFERENT
MIG-29 LPS	DIFFERENT	DIFFERENT
MIRAGE FPS total	DIFFERENT	DIFFERENT
MIRAGE FPS INT	NOT DIFFERENT	NOT DIFFERENT
MIRAGE LPS	NOT DIFFERENT	NOT DIFFERENT
MUDAYSIS FPS	DIFFERENT	DIFFERENT
RED FPS	DIFFERENT	DIFFERENT
RED LPS	DIFFERENT	DIFFERENT
RIYADH FPS	DIFFERENT	DIFFERENT
SHAIBAH FPS	DIFFERENT	DIFFERENT

Looking at the table above we can see that the decision changes only once, and it is highlighted in gray.

Since the change is not consistently positive or negative and the MOEs were selected to reflect a range of aggregation, it seems logical to see if there are any commonalities between the aggregation levels and reduction. When sorted into the different aggregation levels no pattern emerges. The only item of possible note is that the data collected at the squadron level are all positive. When the data is sorted by force, RED and BLUE, there is also no notable pattern.

4.3. Antithetic Variates

A total of 600 replications were performed to analyze the affects of antithetic variates on THUNDER. Table 4.11 details the experiment settings; remember that each set consists of 300 replications. The first 300 replications, set D, were used to generate base confidence intervals for comparison and the first half of the antithetic pairs. The replications were performed with the new RNG, with each random input synchronized with its own stream, and antithetic variates not selected. The second 300 replications, set F, were the second half of the antithetic pairs. The replications were performed with the new RNG, with each random number input synchronized with the replications from set D, and antithetic variates turned on. Turning on antithetic variates forces all of the random numbers to be drawn as $1 -$ the original random number. The 300 antithetic pairs are generated from all 600 replications. The halfwidths were calculated at the $\alpha = 0.05$ level.

Table 4.11: Antithetic Variate Experiment Settings

	RNG	SYNCHRONIZED	ANTITHETIC	COLLECT CV	CONFIGURATION
SET	(NEW/OLD)	(YES/NO)	(YES/NO)	(YES/NO)	(ORIGINAL/MODIFIED)
D	NEW	YES	NO	YES	ORIGINAL
F	NEW	YES	YES	YES	ORIGINAL

The first subsection contains the comparison of the antithetic variates halfwidths with the regular halfwidths. The second subsection contains the calculations to determine the number of replications needed to obtain the variance reduction obtained with antithetic variates. The last subsection highlights insights seen in antithetic analysis.

4.3.1. Normal to Variance Reduction Technique.

To test the reduction in variance, the standard generated halfwidths of the MOEs are compared with the antithetic variate halfwidths of the MOEs. The following table reports the variance reduction due to antithetic variates.

Table 4.12: Antithetic Variate (300 Replication) vs. Replication Reduction

MOE	BASE		ANTITHETIC VARIATES		PERCENT CHANGE
	MEAN	HALFWIDTH	MEAN	HALFWIDTH	
A-10 LPS	0.005145212	0.00028569	0.004980108	0.000214215	-25.02%
A-6 LPS	0.019104498	0.000928243	0.018614329	0.000708626	-23.66%
BLUE FPS	0.582000237	0.002036313	0.581054499	0.001481472	-27.25%
BLUE LPS	0.010170101	0.000174156	0.010111304	0.000112451	-35.43%
BLUE SMG	34474.62	84.52936072	34526.50667	57.67080159	-31.77%
DHAHRAN FPS	0.372019758	0.006733921	0.372211006	0.004820585	-28.41%
F-111 LPS	0.016760015	0.000416308	0.016685204	0.000253913	-39.01%
F-15 LPS	0.006207278	0.00031009	0.006242106	0.000208184	-32.86%
FA-18 FPS TOTAL	0.233627904	0.003723047	0.232053597	0.002729652	-26.68%
FA-18 FPS DCA	0.044337541	0.001389283	0.043733405	0.000830637	-40.21%
MIG-23 LPS	0.257329967	0.006037934	0.257671361	0.004167409	-30.98%
MIG-29 LPS	0.200408126	0.007942862	0.197127827	0.006042087	-23.93%
MIRAGE FPS TOTAL	0.600422202	0.00449042	0.601209538	0.003406191	-24.15%
MIRAGE FPS INT	0.699855667	0.005731393	0.702536288	0.003813333	-33.47%
MIRAGE LPS	0.276394858	0.004501578	0.275381579	0.003051761	-32.21%
MUDAYSIS FPS	0.189549709	0.00488572	0.1887675	0.003383585	-30.75%
RED FPS	0.391872732	0.001772589	0.392056037	0.001094404	-38.26%
RED LPS	0.192619582	0.001692612	0.191275098	0.001079866	-36.20%
RIYADH FPS	0.854947018	0.001535138	0.854861142	0.00111826	-27.16%
SHAIBAH FPS	0.504592164	0.006312332	0.50172746	0.004368135	-30.80%

The reduction in halfwidths in the above table initially looks great, but the fact that the antithetic variates are generated with twice the number of replications may inflate the actual reduction. Therefore, the following antithetic variate vs. replication table was created using only the first 150 antithetic pairs.

Table 4.13: Antithetic Variate (150 Replication) vs. Replication Reduction

MOE	BASE		ANTITHETIC VARIATES		PERCENT CHANGE
	MEAN	HALFWIDTH	MEAN	HALFWIDTH	
A-10 LPS	0.005145212	0.00028569	0.004980108	0.000304497	6.58%
A-6 LPS	0.019104498	0.000928243	0.018614329	0.001007279	8.51%
BLUE FPS	0.582000237	0.002036313	0.581054499	0.002105844	3.41%
BLUE LPS	0.010170101	0.000174156	0.010111304	0.000159844	-8.22%
BLUE SMG	34474.62	84.52936072	34526.50667	81.9763507	-3.02%
DHAHRAN FPS	0.372019758	0.006733921	0.372211006	0.006852237	1.76%
F-111 LPS	0.016760015	0.000416308	0.016685204	0.000360925	-13.30%
F-15 LPS	0.006207278	0.00031009	0.006242106	0.000295924	-4.57%
FA-18 FPS TOTAL	0.233627904	0.003723047	0.232053597	0.003880073	4.22%
FA-18 FPS DCA	0.044337541	0.001389283	0.043733405	0.001180712	-15.01%
MIG-23 LPS	0.257329967	0.006037934	0.257671361	0.005923777	-1.89%
MIG-29 LPS	0.200408126	0.007942862	0.197127827	0.008588544	8.13%
MIRAGE FPS TOTAL	0.600422202	0.00449042	0.601209538	0.004841742	7.82%
MIRAGE FPS INT	0.699855667	0.005731393	0.702536288	0.005420474	-5.42%
MIRAGE LPS	0.276394858	0.004501578	0.275381579	0.004337935	-3.64%
MUDAYSIS FPS	0.189549709	0.00488572	0.1887675	0.004809609	-1.56%
RED FPS	0.391872732	0.001772589	0.392056037	0.001555645	-12.24%
RED LPS	0.192619582	0.001692612	0.191275098	0.001534979	-9.31%
RIYADH FPS	0.854947018	0.001535138	0.854861142	0.001589555	3.54%
SHAIBAH FPS	0.504592164	0.006312332	0.50172746	0.006209099	-1.64%

Now, with the number of replications used to generate the base and antithetic pairs being equal, the reduction becomes mixed. The halfwidth reductions are highlighted above.

4.3.2. Variance Reduction Technique to Number of Replications.

The reduction gained can also be seen by calculating the number of replications needed to achieve the antithetic variate halfwidth. To do this, the halfwidth calculation is iterated by incrementing the number of replications in the equation until the halfwidth is smaller than the antithetic variate halfwidth. A major assumption to this method is the variance remains constant. The following table displays the number of replications needed to achieve the variance reduction with the 300 antithetic pairs.

Table 4.14: Replications Needed to Achieve Antithetic Variate Reduction (300 Replications)

MOE	REPLICATIONS	CHANGE IN REPLICATIONS	PERCENT CHANGE
A-10 LPS	532	232	77.33%
A-6 LPS	513	213	71.00%
BLUE FPS	565	265	88.33%
BLUE LPS	716	416	138.67%
BLUE SMG	642	342	114.00%
DHAHRAN FPS	583	283	94.33%
F-111 LPS	802	502	167.33%
F-15 LPS	662	362	120.67%
FA-18 FPS total	556	256	85.33%
FA-18 FPS DCA	834	534	178.00%
MIG-23 LPS	627	327	109.00%
MIG-29 LPS	517	217	72.33%
MIRAGE FPS total	520	220	73.33%
MIRAGE FPS INT	674	374	124.67%
MIRAGE LPS	650	350	116.67%
MUDAYSIS FPS	623	323	107.67%
RED FPS	783	483	161.00%
RED LPS	733	433	144.33%
RIYADH FPS	563	263	87.67%
SHAIBAH FPS	624	324	108.00%

Note above, that not all of the replication increases are greater than or equal to the 300 extra replications needed to create the antithetic pairs. The following table is a better representation of the number of the number of replications needed to achieve the variance reduction. It uses the antithetic variates with the 150 replications.

Table 4.15: Replications Needed to Achieve Antithetic Variate Reduction (150 Replications)

MOE	REPLICATIONS	CHANGE IN REPLICATIONS	PERCENT CHANGE
A-10 LPS	265	-35	-11.67%
A-6 LPS	256	-44	-14.67%
BLUE FPS	281	-19	-6.33%
BLUE LPS	356	56	18.67%
BLUE SMG	319	19	6.33%
DHAHRAN FPS	290	-10	-3.33%
F-111 LPS	399	99	33.00%
F-15 LPS	330	30	10.00%
FA-18 FPS total	277	-23	-7.67%
FA-18 FPS DCA	415	115	38.33%
MIG-23 LPS	312	12	4.00%
MIG-29 LPS	258	-42	-14.00%
MIRAGE FPS total	259	-41	-13.67%
MIRAGE FPS INT	336	36	12.00%
MIRAGE LPS	323	23	7.67%
MUDAYSIS FPS	310	10	3.33%
RED FPS	389	89	29.67%
RED LPS	365	65	21.67%
RIYADH FPS	281	-19	-6.33%
SHAIBAH FPS	310	10	3.33%

As seen in the previous section, not all halfwidths are reduced. Also, note that the MOEs in Table 4.14, that have an increase less than 300, are the same MOEs in the table above that have increases.

4.3.3. Antithetic Variates Insights.

As with common random numbers, since the reduction is not always positive, a search for commonalities between the aggregation levels and reduction could be fruitful. When sorted into the different aggregation levels no pattern emerges. Also, when sorted by force, RED and BLUE, no pattern emerges.

4.4. Control Variates and Antithetic Variates

The same 600 replications used for antithetic variates were also used for the combination of control variates and antithetic variates. Table 4.16 details the experiment

settings; remember that each set consists of 300 replications. The first 300 replications, set D, were used to generate base confidence intervals for comparison and the first half of the antithetic pairs. The replications were performed with the new RNG, with each random input synchronized with its own stream, and antithetic variates not selected. The second 300 replications, set F, were the second half of the antithetic pairs. The replications were performed with the new RNG, with each random number input synchronized with the replications from set D, and antithetic variates turned on. Turning on antithetic variates forces all of the random numbers to be drawn as 1 – the original random number. The only difference is that control variates are used to reduce the variance. The halfwidths were calculated with at the $\alpha = 0.05$ level.

Table 4.16: Antithetic Variate / Control Variate Experiment Settings

	RNG	SYNCHRONIZED	ANTITHETIC	COLLECT CV	CONFIGURATION
SET	(NEW/OLD)	(YES/NO)	(YES/NO)	(YES/NO)	(ORIGINAL/MODIFIED)
D	NEW	YES	NO	YES	ORIGINAL
F	NEW	YES	YES	YES	ORIGINAL

The first subsection contains the comparison of the base halfwidths to the control variate and antithetic variate reduction. The second subsection contains an analysis of the number of replications needed to achieve the control variate and antithetic variate reduction. The last subsection contains insights obtained by using antithetic variates in combination with control variates.

4.4.1. Normal to Variance Reduction Technique.

To test the reduction in variance, the standard generated halfwidths of the MOEs are compared with the antithetic variate halfwidths of the MOEs reduced even further by also applying the control variate technique. The following table reports the variance reduction due to antithetic variates and control variates.

Table 4.17: Control Variate and Antithetic Variate (300 Replication) vs. Replication Reduction

MOE	BASE		AV / CV		PERCENT CHANGE
	MEAN	HALFWIDTH	MEAN	HALFWIDTH	
A-10 LPS	0.005145212	0.00028569	0.004999208	0.000195998	-31.40%
A-6 LPS	0.019104498	0.000928243	0.01877966	0.000687489	-25.94%
BLUE FPS	0.582000237	0.002036313	0.580978958	0.001410833	-30.72%
BLUE LPS	0.010170101	0.000174156	0.010142479	0.000115121	-33.90%
BLUE SMG	34474.62	84.52936072	34473.68258	61.43489655	-27.32%
DHAHRAN FPS	0.372019758	0.006733921	0.369991922	0.004627463	-31.28%
F-111 LPS	0.016760015	0.000416308	0.016805487	0.000266501	-35.98%
F-15 LPS	0.006207278	0.00031009	0.006329536	0.00020287	-34.58%
FA-18 FPS TOTAL	0.233627904	0.003723047	0.232572805	0.002590169	-30.43%
FA-18 FPS DCA	0.044337541	0.001389283	0.044025386	0.000931742	-32.93%
MIG-23 LPS	0.257329967	0.006037934	0.256304079	0.004466771	-26.02%
MIG-29 LPS	0.200408126	0.007942862	0.198779022	0.005634799	-29.06%
MIRAGE FPS TOTAL	0.600422202	0.00449042	0.600109645	0.003195737	-28.83%
MIRAGE FPS INT	0.699855667	0.005731393	0.700002069	0.003816317	-33.41%
MIRAGE LPS	0.276394858	0.004501578	0.276342171	0.002949469	-34.48%
MUDAYSIS FPS	0.189549709	0.00488572	0.189966945	0.003417543	-30.05%
RED FPS	0.391872732	0.001772589	0.391871895	0.001191619	-32.78%
RED LPS	0.192619582	0.001692612	0.192330512	0.001167319	-31.03%
RIYADH FPS	0.854947018	0.001535138	0.854828925	0.001071476	-30.20%
SHAIBAH FPS	0.504592164	0.006312332	0.505066145	0.004503055	-28.66%

Again, this reduction is created with a total of 600 replications, double the number of replications used for the base case. The next table is the reduction due to antithetic variates using only the first 150 antithetic pairs and control variates.

Table 4.18: Control Variate and Antithetic Variate (150 Replication) vs. Replication Reduction

MOE	BASE		AV/CV		PERCENT CHANGE
	MEAN	HALFWIDTH	MEAN	HALFWIDTH	
A-10 LPS	0.005145212	0.00028569	0.005038231	0.000292638	2.43%
A-6 LPS	0.019104498	0.000928243	0.018696752	0.00100282	8.03%
BLUE FPS	0.582000237	0.002036313	0.581084169	0.002088085	2.54%
BLUE LPS	0.010170101	0.000174156	0.010110917	0.000156743	-10.00%
BLUE SMG	34474.62	84.52936072	34547.7152	80.62975389	-4.61%
DHAHRAN FPS	0.372019758	0.006733921	0.370927039	0.006942557	3.10%
F-111 LPS	0.016760015	0.000416308	0.016744672	0.00034699	-16.65%
F-15 LPS	0.006207278	0.00031009	0.006303071	0.000289469	-6.65%
FA-18 FPS TOTAL	0.233627904	0.003723047	0.231209234	0.003892977	4.56%
FA-18 FPS DCA	0.044337541	0.001389283	0.043528432	0.001156129	-16.78%
MIG-23 LPS	0.257329967	0.006037934	0.257478208	0.005841578	-3.25%
MIG-29 LPS	0.200408126	0.007942862	0.194782302	0.007954705	0.15%
MIRAGE FPS TOTAL	0.600422202	0.00449042	0.600955714	0.004651799	3.59%
MIRAGE FPS INT	0.699855667	0.005731393	0.702804931	0.005358865	-6.50%
MIRAGE LPS	0.276394858	0.004501578	0.27581175	0.004245828	-5.68%
MUDAYSIS FPS	0.189549709	0.00488572	0.189203986	0.00448441	-8.21%
RED FPS	0.391872732	0.001772589	0.392220779	0.001535464	-13.38%
RED LPS	0.192619582	0.001692612	0.191270973	0.001510308	-10.77%
RIYADH FPS	0.854947018	0.001535138	0.854997708	0.001574458	2.56%
SHAIBAH FPS	0.504592164	0.006312332	0.501744195	0.006108584	-3.23%

Again, the reduction is mixed and the reduced halfwidths are highlighted. When compared to the regular antithetic variates, the halfwidth reduction is larger and the halfwidth increase is smaller.

4.4.2. Variance Reduction Technique to Number of Replications.

Another way to represent the reduction realized from the combination of control variates and antithetic variates is seen by calculating the number of replications needed to achieve the control variate and antithetic variate halfwidth. To do this, the halfwidth calculation is iterated by incrementing the number of replications in the equation until the halfwidth is smaller than the antithetic variate halfwidth. A major assumption to this method is the variance remains constant. The following table displays the number of

replications needed to achieve the variance reduction created by the 300 replication antithetic variates and control variates.

Table 4.19: Replications Needed to Achieve Control Variate and Antithetic Variate Reduction (300 replications)

MOE	REPLICATIONS	CHANGE IN REPLICATIONS	PERCENT CHANGE
A-10 LPS	635	335	111.67%
A-6 LPS	545	245	81.67%
BLUE FPS	622	322	107.33%
BLUE LPS	683	383	127.67%
BLUE SMG	566	266	88.67%
DHAHRAN FPS	632	332	110.67%
F-111 LPS	728	428	142.67%
F-15 LPS	697	397	132.33%
FA-18 FPS total	617	317	105.67%
FA-18 FPS DCA	664	364	121.33%
MIG-23 LPS	546	246	82.00%
MIG-29 LPS	594	294	98.00%
MIRAGE FPS total	590	290	96.67%
MIRAGE FPS INT	673	373	124.33%
MIRAGE LPS	695	395	131.67%
MUDAYSIS FPS	610	310	103.33%
RED FPS	661	361	120.33%
RED LPS	628	328	109.33%
RIYADH FPS	613	313	104.33%
SHAIBAH FPS	587	287	95.67%

Note again, that not all of the replication increases are greater than or equal to the 300 extra replications needed to create the antithetic variates. The following table displays the number of replications needed to achieve the halfwidth generated by the combination of control variates and antithetic variates with the 150 antithetic pairs.

Table 4.20: Replications Needed to Achieve Control Variate and Antithetic Variate Reduction (150 replications)

MOE	REPLICATIONS	CHANGE IN REPLICATIONS	PERCENT CHANGE
A-10 LPS	287	-13	-4.33%
A-6 LPS	258	-42	-14.00%
BLUE FPS	286	-14	-4.67%
BLUE LPS	370	70	23.33%
BLUE SMG	330	30	10.00%
DHAHRAN FPS	283	-17	-5.67%
F-111 LPS	431	131	43.67%
F-15 LPS	344	44	14.67%
FA-18 FPS total	275	-25	-8.33%
FA-18 FPS DCA	432	132	44.00%
MIG-23 LPS	321	21	7.00%
MIG-29 LPS	300	0	0.00%
MIRAGE FPS total	280	-20	-6.67%
MIRAGE FPS INT	343	43	14.33%
MIRAGE LPS	337	37	12.33%
MUDAYSIS FPS	356	56	18.67%
RED FPS	399	99	33.00%
RED LPS	377	77	25.67%
RIYADH FPS	286	-14	-4.67%
SHAIBAH FPS	321	21	7.00%

4.4.3. Combined Antithetic Variate and Control Variate Insight.

Since the control variate technique is applied to the antithetic variates, information can be gleaned as in section 4.1.3 Control Variate Insight. A list of statistically significant controls related to the MOEs from the 150-replication antithetic pairs is below.

**Table 4.21: Antithetic Variate and Control Variate Statistically Significant Controls
Table (150 Replications)**

MOE	WEIGHT	CONTROL	MOE	WEIGHT	CONTROL
A-10 LPS	-0.0077	__AIR911_1	MIG-29 LPS	15.1554	__ADF140_3
	0.0082	__AIR911_2		-1.2270	__AIR101_1
	0.2273	__ISR000_4		33.4814	__AIR840_2
A-6 LPS	2.8138	__UTL104_1		-4.4824	__ISR000_3
BLUE FPS	-0.0542	__AIR911_1		-36.7484	__UTL104_1
BLUE LPS	0.3643	__AIR007_1	MIRAGE FPS	0.0583	__AIR070_1
BLUE SMG	33390.9611	__ADF150_5	TOTAL	0.0006	__AIR567_2
	-112989.0889	__AIR528_1		-7.0484	__BSE003_1
DHAHRAN FPS	17.9111	__ADF121_1	MIRAGE FPS INT	0.8158	__AIR050_1
F-111 LPS	-0.2916	__AIR550_2	MIRAGE LPS	-13.9508	__AIR840_2
	1.5291	__BSE200_5		6.8540	__BSE003_1
	0.9901	__GRD100_1	MUDAYSIS FPS	-10.8821	__ADF140_3
F-15 LPS	0.0968	__ADF150_5		10.0131	__AIR007_1
	0.2306	__AIR550_2		0.0405	__AIR070_1
	0.3501	__BSE050_2		0.0007	__AIR567_2
FA-18 FPS	11.4841	__ADF121_1			-14.8256
TOTAL	1.2846	__AIR101_2		24.6841	__BSE200_5
FA-18 FPS DCA	-0.0034	__AIR060_2	RED FPS	0.9477	__BSE400_1
	0.0146	__AIR800_3		0.6997	__ISR000_3
MIG-23 LPS	0.0637	__AIR070_1	RED LPS	-0.8878	__ISR000_3
			RIYADH FPS	0.9135	__ISR000_4
			SHAIBAH FPS	3.6016	__ISR000_3

As seen with the CV, these weights and controls can be used to give the analyst a better understanding of how the simulation works. The following table, Table 4.22, examines the MOE MUDAYSIS FPS (Flown per Planned Sortie). It can be seen that the statistically significant controls are ADF140.3, AIR007.1, AIR070.1, AIR567.2, AIR840.2, and BSE200.5. Note, AIR007.1 is a random input that is miss labeled. It should be in AIR007.sim, but it is located in AIR014.1.

Table 4.22: Antithetic Variate and Control Variate Purpose of Statistically Significant Controls

CONTROL	WEIGHT	MODULE PURPOSE	SPECIFIC DRAW PURPOSE
ADF140_3	-10.8821	Calculates, for each air defense type, the number of engaged sites and rounds fired per site for primaries.	Used determine the actual number of sites engaging as a function of FRAC.INTEGRATED (used to measure command and control). $(U(0,1) < \text{frac.f}(\text{engaged.shooters}))$
AIR007_1	10.0131	Continue a flight after the air-to-air refueling decision has been made.	Used to determine the launching of interceptors. $(U(0,1) \leq \text{TA.PROB.ENEMY.INT.LAUNCH})$
AIR070_1	0.0405	Adjudicate a defensive anti tactical ballistic missile mission VS. tactical ballistic missile (TBM) air-to-air engagement.	Used to determine determine TBM flight phase (and pK) at which to adjudicate. (distribution) Used to determine duration of airborne laser shot duration.
AIR567_2	0.0007	Compute target location error for an offensive anti tactical ballistic missile mission (OTBM) flight group which has arrived at its target.	Generate meters error from a normal distribution. (distribution)
AIR840_2	-14.8256	Determine the number of target elements that are destroyed when a given weapons area of effect fully or partially covers a target.	Determine how many live target elements were hit. $(U(0,1) < \text{PROB.HIT.LIVE})$
BSE200_5	24.6841	Determine maintenance tasks to be performed on aircraft in the given flight and schedule those for which resources are currently available. Print warning when required non-consumable resource is not available at squadron's mob.	Used to build list of maintenance tasks required. $(U(0,1) \leq \text{TA.PROB.LONG.TERM.REPAIR})$

Using the chart above, a number of system characteristics can be determined.

First, an increase in the number of engaged air defense shooters would decrease MUDAYSIS FPS. Second, a decrease in the launching of interceptors would decrease MUDAYSIS FPS. Third, a decrease in the airborne laser shot duration required will slightly decrease MUDAYSIS FPS. Fourth, a decrease in the normal error of an OTBM (Offensive Anti Tactical Ballistic Missile Mission) will slightly decrease MUDAYSIS FPS. Fifth, an increase in the number of live targets hit will decrease MUDAYSIS FPS.

Sixth, the increase in the long-term repairs, will greatly decrease MUDAYSIS FPS.

Overall, it seems that an increase in engagement will decrease the number of flown per planned sorties. This same analysis can be applied to the control variates related to other MOEs.

As with common random numbers, since the reduction is not always positive, a search for commonalities between the aggregation levels and reduction could be fruitful. When sorted into the different aggregation levels no pattern emerges. Also, when sorted by force, no pattern emerges.

4.5. Control Variates and Common Random Numbers

To analyze the effectiveness of combining CV and CRN techniques, a total of 1200 replications were performed. Table 4.8 details the experiment settings; remember that each set consists of 300 replications. The sets can be separated into two groups. The first group is the standard independent data that makes up the base data and the second group is the partially synchronized data. All replications were of the standard ME scenario, using the new RNG. The first 300 replications, set M, contained no changes to the database and with all random inputs using a single stream for each replication. The second 300 replications, set O, were performed with all of the F-111s removed from the database and with all random inputs using the same single streams applied to set B. The third 300 replications, set S, contained no changes to the database and were performed with selected random inputs synchronized therefore, receiving their own random number stream in each replication and the rest independent. The last 300 replications, set T, were performed with all of the F-111s removed from the database and with the selected random inputs synchronized with set S and the rest independent.

Table 4.23: Control Variate and Common Random Number Experiment Settings

	RNG	SYNCHRONIZED	ANTITHETIC	COLLECT CV	CONFIGURATION
SET	(NEW/OLD)	(YES/NO)	(YES/NO)	(YES/NO)	(ORIGINAL/MODIFIED)
M	NEW	NO*	NO	YES	ORIGINAL
O	NEW	NO*	NO	YES	MODIFIED
S	NEW	YES*	NO	YES	ORIGINAL
T	NEW	YES*	NO	YES	MODIFIED

The following analysis compares the halfwidths generated by calculating the difference between scenario configurations. The first comparison is by the standard method, not synchronized, and the second comparison is by combining CRN with selected synchronization and CV. The second section highlights insights gleaned from using CRN.

4.5.1. Normal to Variance Reduction Technique.

The paired-t CI at the $\alpha = 0.05$ level was used to determine whether the MOEs generated from a configuration change in the ME scenario resulted in statistically different values. Then the paired-t halfwidths were compared to determine the reduction in variance. The following table displays the results of this comparison.

Table 4.24: Control Variate and Common Random Number Halfwidth Reduction

MOE	BASE		CV/CRN		PERCENT CHANGE
	MEAN	HALFWIDTH	MEAN	HALFWIDTH	
A-10 LPS	-0.005074435	0.000471166	-0.005420376	0.000495875	5.24%
A-6 LPS	-0.003709347	0.001243332	-0.003862475	0.001142089	-8.14%
BLUE FPS	0.080204272	0.002488093	0.078021187	0.002276083	-8.52%
BLUE LPS	-0.000980203	0.000224242	-0.001228896	0.000216219	-3.58%
BLUE SMG	321.6566667	92.75065974	283.8370489	94.46705704	1.85%
DHAHRAN FPS	0.047497651	0.00785785	0.043664487	0.007499356	-4.56%
F-15 LPS	-0.00029301	0.000348631	-0.000778342	0.00039424	13.08%
FA-18 FPS total	0.023885856	0.004348857	0.021403974	0.004115626	-5.36%
FA-18 FPS DCA	9.37616E-05	0.001776789	-0.002378309	0.001642749	-7.54%
MIG-23 LPS	0.00720557	0.009116531	0.002253995	0.008420355	-7.64%
MIG-29 LPS	0.058508654	0.008627634	0.058072515	0.008322543	-3.54%
MIRAGE FPS total	0.008655135	0.005768579	0.001181363	0.00581596	0.82%
MIRAGE FPS INT	-0.004831629	0.006898662	-0.001808304	0.007049026	2.18%
MIRAGE LPS	-0.000117038	0.00564862	0.005595717	0.005615011	-0.60%
MUDAYSIS FPS	0.071070466	0.00554528	0.066758129	0.005276546	-4.85%
RED FPS	0.034613556	0.002097873	0.030483796	0.002043576	-2.59%
RED LPS	0.022702029	0.002120665	0.02316245	0.002015068	-4.98%
RIYADH FPS	-0.072184072	0.001689959	-0.072668778	0.001737694	2.82%
SHAIBAH FPS	0.093599432	0.008845515	0.095513973	0.008256205	-6.66%

Looking above, we can see that the halfwidth is not always smaller. The changes highlighted above are the halfwidths that are reduced. This implies that there is not always a reduction in the variance when combining CV and CRN. Knowing from section 4.2, that CRN does not always reduce the halfwidth, the control variate estimator is applied to the independent base data set to determine the effect due to CV. The following table is the result.

Table 4.25: Control Variate Only Halfwidth Reduction

MOE	BASE		CV		PERCENT CHANGE
	MEAN	HALFWIDTH	MEAN	HALFWIDTH	
A-10 LPS	-0.005074435	0.000471166	-0.00506369	0.000464018	-1.52%
A-6 LPS	-0.003709347	0.001243332	-0.003673866	0.001221513	-1.75%
BLUE FPS	0.080204272	0.002488093	0.080081841	0.002427363	-2.44%
BLUE LPS	-0.000980203	0.000224242	-0.000971024	0.000219306	-2.20%
BLUE SMG	321.6566667	92.75065974	322.6088152	92.30977839	-0.48%
DHAHRAN FPS	0.047497651	0.00785785	0.047189217	0.007795751	-0.79%
F-15 LPS	-0.00029301	0.000348631	-0.000292464	0.000345254	-0.97%
FA-18 FPS total	0.023885856	0.004348857	0.023798247	0.004325066	-0.55%
FA-18 FPS DCA	9.37616E-05	0.001776789	0.000161301	0.001764302	-0.70%
MIG-23 LPS	0.00720557	0.009116531	0.006046667	0.008687175	-4.71%
MIG-29 LPS	0.058508654	0.008627634	0.058064528	0.008499025	-1.49%
MIRAGE FPS total	0.008655135	0.005768579	0.009424086	0.005625573	-2.48%
MIRAGE FPS INT	-0.004831629	0.006898662	-0.005030783	0.006825481	-1.06%
MIRAGE LPS	-0.000117038	0.00564862	-0.000991526	0.005563242	-1.51%
MUDAYSIS FPS	0.071070466	0.00554528	0.071135554	0.005548611	0.06%
RED FPS	0.034613556	0.002097873	0.034764827	0.002032008	-3.14%
RED LPS	0.022702029	0.002120665	0.02226502	0.002083652	-1.75%
RIYADH FPS	-0.072184072	0.001689959	-0.072522867	0.001643588	-2.74%
SHAIBAH FPS	0.093599432	0.008845515	0.096093296	0.008691198	-1.74%

Note, that almost all of the halfwidths are reduced. This implies that the majority variance increases are due to the application of CRN.

4.5.2. Combined Control Variate and Common Random Number Insight.

As can be seen with CRN, the decision of whether the MOE results between configurations are statistically different or not, may change between the base non-synchronized and the synchronized, as a result from both the change in halfwidth and a shift in the mean value. The following table displays the decision results among the MOEs and identifies any changes in the decisions between the base and synchronized results. Each of the CIs developed for the MOEs below are calculated at the $\alpha = 0.05$ level and are calculated separately.

Table 4.26: Control Variate and Common Random Number Configuration Decision

MOE	BASE DECISION	CV/CRN DECISION
A-10 LPS	DIFFERENT	DIFFERENT
A-6 LPS	DIFFERENT	DIFFERENT
BLUE FPS	DIFFERENT	DIFFERENT
BLUE LPS	DIFFERENT	DIFFERENT
BLUE SMG	DIFFERENT	DIFFERENT
DHAHRAN FPS	DIFFERENT	DIFFERENT
F-15 LPS	NOT DIFFERENT	DIFFERENT
FA-18 FPS total	DIFFERENT	DIFFERENT
FA-18 FPS DCA	NOT DIFFERENT	DIFFERENT
MIG-23 LPS	NOT DIFFERENT	NOT DIFFERENT
MIG-29 LPS	DIFFERENT	DIFFERENT
MIRAGE FPS total	DIFFERENT	NOT DIFFERENT
MIRAGE FPS INT	NOT DIFFERENT	NOT DIFFERENT
MIRAGE LPS	NOT DIFFERENT	NOT DIFFERENT
MUDAYSIS FPS	DIFFERENT	DIFFERENT
RED FPS	DIFFERENT	DIFFERENT
RED LPS	DIFFERENT	DIFFERENT
RIYADH FPS	DIFFERENT	DIFFERENT
SHAIBAH FPS	DIFFERENT	DIFFERENT

Looking at the table above, we can see that the decision changes three times and they are highlighted in gray.

Since the change is not consistently positive or negative and the MOEs were selected to reflect a range of aggregation, it seems logical to see if there are any commonalities between the aggregation levels and reduction. When sorted into the different aggregation levels no pattern emerges. The only item of possible note is that the data collected at the squadron level are all positive. When the data is sorted by force, RED and BLUE, there is also no notable pattern.

4.6. Random Number Generator Comparison

To perform the CRN analysis a new RNG needed to be implemented. The research in generating this new RNG proclaims that it has better statistical properties and its speed is faster (16). For the application in THUNDER, a more important question is

not how good the statistical properties are, but are the results statistically different from the original RNG and do replications using the new RNG take longer to run. To test these questions, three different comparisons were conducted. To perform the comparisons, paired-t CIs were developed for all MOEs at the $\alpha = 0.05$ level. Since all MOEs and time are compared simultaneously, application of the Bonferroni inequality is used to maintain the $\alpha = 0.05$ level throughout all MOEs and time comparisons.

Table 4.27: Random Number Experiment Settings

	RNG	SYNCHRONIZED	ANTITHETIC	COLLECT CV	CONFIGURATION
SET	(NEW/OLD)	(YES/NO)	(YES/NO)	(YES/NO)	(ORIGINAL/MODIFIED)
B	NEW	NO	NO	NO	ORIGINAL
G	OLD	NO	NO	NO	ORIGINAL
H	NEW	YES	NO	NO	ORIGINAL

The table above displays the experiment settings used for the comparisons; remember that each set was performed with 300 replications. The first subsection contains a comparison between the original RNG and the new RNG. This comparison uses sets B and G from the table above. The next subsection contains a comparison between the original RNG and the new RNG with synchronized random inputs. Generating a unique stream for each random input. This comparison uses sets G and H from the above table. The last subsection contains a comparison between the new RNG, not synchronized, and the new RNG with synchronized random inputs. This comparison uses sets B and H from the table above.

4.6.1. Original vs. New (not synchronized) Random Number Generator.

Confidence intervals were created for a comparison to decide if the new RNG is statistically different from the original RNG. The following table and graph depicts the confidence intervals and determines which, if any, are statistically different.

Table 4.28: Original vs. New (not synchronized) Random Number Generator

MOE	LOWER BOUND	UPPER BOUND	CONTAINS ZERO
A-10 LPS	-0.000673185	0.000498496	YES
A-6 LPS	-0.002034542	0.001989532	YES
BLUE FPS	-0.004493169	0.00452297	YES
BLUE LPS	-0.000380992	0.000266721	YES
BLUE SMG	-206.0933947	143.946728	YES
DHAHRAN FPS	-0.013936772	0.016032878	YES
F-111 LPS	-0.000871293	0.000863446	YES
F-15 LPS	-0.000541279	0.00066419	YES
FA-18 FPS total	-0.009697343	0.006429048	YES
FA-18 FPS DCA	-0.004787346	0.000840694	YES
MIG-23 LPS	-0.01238682	0.013461924	YES
MIG-29 LPS	-0.013436245	0.018160475	YES
MIRAGE FPS total	-0.011752971	0.007611029	YES
MIRAGE FPS INT	-0.009436666	0.015837388	YES
MIRAGE LPS	-0.006410013	0.011816126	YES
MUDAYSIS FPS	-0.012006375	0.009409523	YES
RED FPS	-0.005130225	0.002138004	YES
RED LPS	-0.002755065	0.004516344	YES
RIYADH FPS	-0.002162778	0.004127981	YES
SHAIBAH FPS	-0.016117409	0.009644726	YES
TIME	-0.184111452	0.070778119	YES

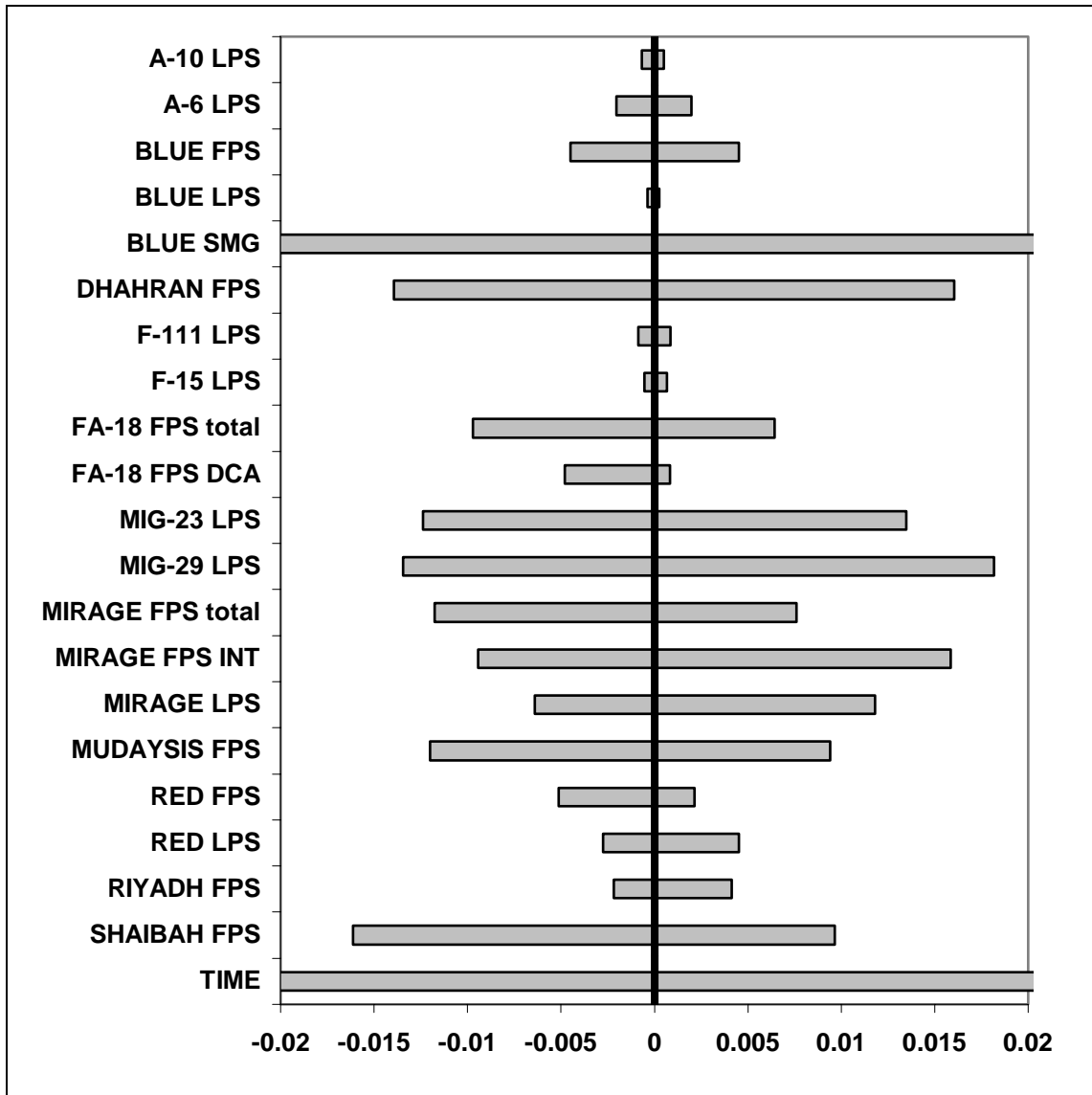


Figure 4.6: Original vs. New (not synchronized) Random Number Generator Confidence Intervals

Notice how all of the confidence intervals contain zero. Statistically, there is no difference in the output form the original RNG and the new (not synchronized) RNG.

4.6.2. Original vs. New (synchronized) Random Number Generators.

Confidence intervals were created for a comparison to decide if the new RNG, when synchronized for CRN, is statistically different from the original RNG. The

following table and graph depicts the confidence intervals and determines which, if any, are statistically different.

Table 4.29: Original vs. New (synchronized) Random Number Generator

MOE	LOWER BOUND	UPPER BOUND	CONTAINS ZERO
A-10 LPS	-0.000776407	0.000343213	YES
A-6 LPS	-0.002242076	0.00172037	YES
BLUE FPS	-0.004762879	0.003842456	YES
BLUE LPS	-0.000279397	0.000398031	YES
BLUE SMG	-160.3646513	186.0646513	YES
DHAHRAN FPS	-0.012801006	0.016895777	YES
F-111 LPS	-0.000626852	0.001139557	YES
F-15 LPS	-0.000401774	0.000842377	YES
FA-18 FPS total	-0.009003699	0.006424452	YES
FA-18 FPS DCA	-0.003217184	0.002117636	YES
MIG-23 LPS	-0.016939633	0.008871754	YES
MIG-29 LPS	-0.01958925	0.009883308	YES
MIRAGE FPS total	-0.011330577	0.006628967	YES
MIRAGE FPS INT	-0.008677052	0.014232686	YES
MIRAGE LPS	-0.010454198	0.00760329	YES
MUDAYSIS FPS	-0.007141542	0.012470464	YES
RED FPS	-0.003830793	0.003359536	YES
RED LPS	-0.003990189	0.002962869	YES
RIYADH FPS	-0.002425742	0.003669871	YES
SHAIBAH FPS	-0.017991997	0.007191441	YES
TIME	-0.219334662	0.052667995	YES

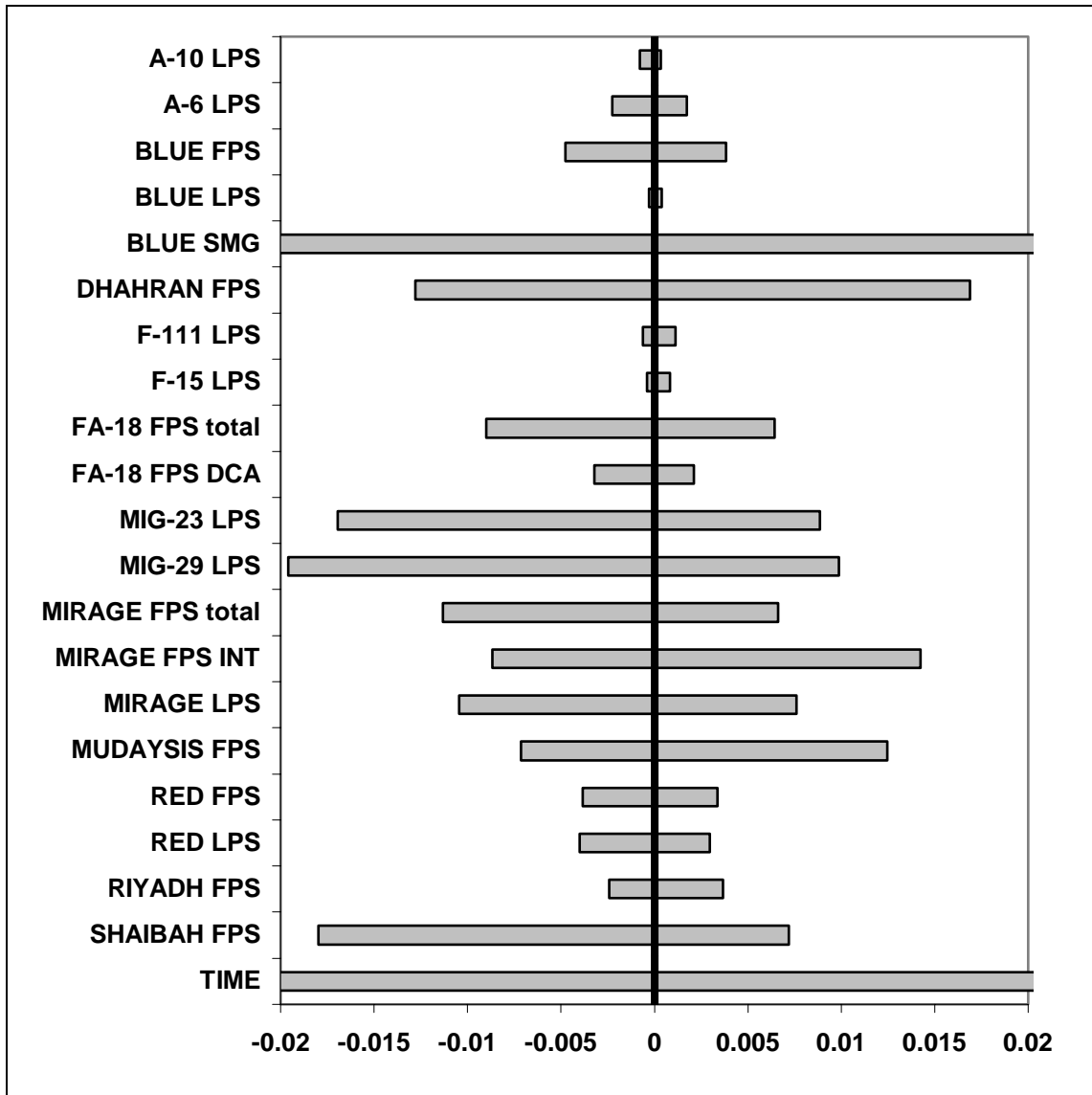


Figure 4.7: Original vs. New (synchronized) Random Number Generator Confidence Intervals

Notice how all of the confidence intervals contain zero. Statistically, there is no difference in the output form the original RNG and the new (synchronized) RNG.

4.6.3. New (not synchronized) vs. New (synchronized) Random Number Generators.

Confidence intervals were created for a comparison to decide if the new RNG, when synchronized for CRN, is statistically different from the new RNG, when not

synchronized for CRN. The following table and graph depicts the confidence intervals and determines which, if any, are statistically different.

Table 4.30: New (not synchronized) vs. New (synchronized) Random Number Generator

MOE	LOWER BOUND	UPPER BOUND	CONTAINS ZERO
A-10 LPS	-0.00074143	0.000482925	YES
A-6 LPS	-0.002085688	0.001608992	YES
BLUE FPS	-0.004700458	0.003750234	YES
BLUE LPS	-0.000235073	0.000467977	YES
BLUE SMG	-122.4487384	210.295405	YES
DHAHRAN FPS	-0.01372776	0.015726424	YES
F-111 LPS	-0.000617935	0.001138486	YES
F-15 LPS	-0.000473583	0.000791275	YES
FA-18 FPS total	-0.007783706	0.008472755	YES
FA-18 FPS DCA	-0.001374783	0.004221887	YES
MIG-23 LPS	-0.016885089	0.007742106	YES
MIG-29 LPS	-0.022430556	0.008000384	YES
MIRAGE FPS total	-0.010063659	0.009503992	YES
MIRAGE FPS INT	-0.012372388	0.011527301	YES
MIRAGE LPS	-0.013056713	0.004799694	YES
MUDAYSIS FPS	-0.006391227	0.014317001	YES
RED FPS	-0.002442988	0.004963952	YES
RED LPS	-0.00493556	0.00214696	YES
RIYADH FPS	-0.003442907	0.002721834	YES
SHAIBAH FPS	-0.015273159	0.010945286	YES
TIME	-0.146257618	0.092924284	YES

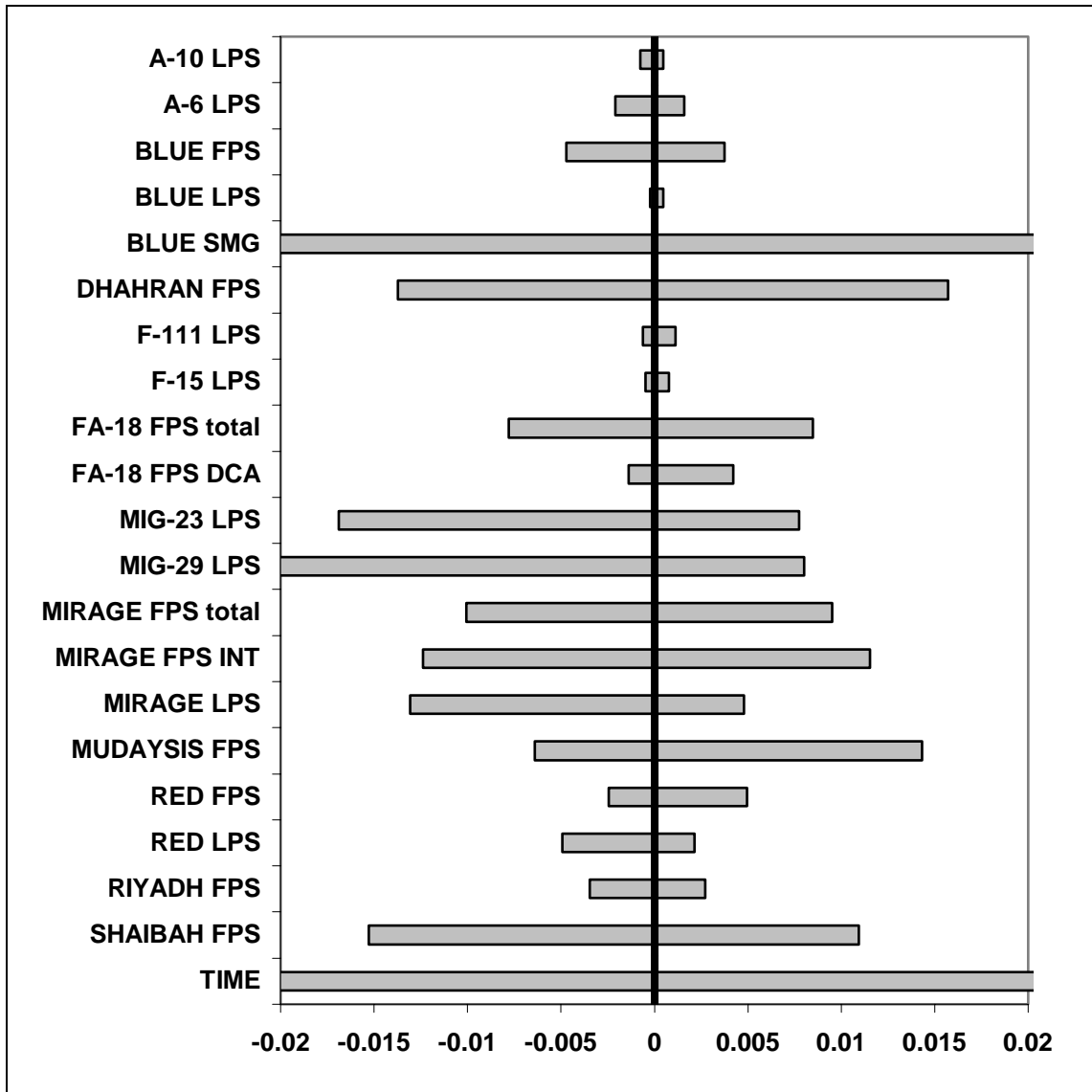


Figure 4.8 New (not synchronized) vs. New (synchronized) Random Number Generator Confidence Intervals

Notice how all of the confidence intervals contain zero. Statistically, there is no difference in the output from the new RNG (not synchronized) and the new (synchronized) RNG.

The following chapter concludes the analysis from this chapter. It develops usable results from this analysis and presents future work in these areas.

5. Conclusion

This section contains all of the conclusions and recommendations from this research. It begins with conclusions derived from the analysis of chapter 4. It then covers some recommendations for further work or study.

5.1. Conclusions

5.1.1. Control Variates.

Of all the variance reduction techniques applied to THUNDER, control variates have performed the best. It consistently realized a reduction in the halfwidths for all MOEs studied, is relatively easy to implement, can be used to reduce the required number of replications, and give valuable insight into the model. The consistency in the halfwidth reduction allows a postprocessor to automatically apply control variates and give a reduced halfwidth without worry of possibly increasing the halfwidth. The ease of implementation also allows a postprocessor to apply control variates without the direct monitoring of the analyst. With a halfwidth goal, use of control variates will reduce the number of replication needed and in turn reduce the time required to analyze the model. Use of the insight given by the weight and sign of the controls can help identify inconsistencies of the code or methodology. It can also aid in understanding how elements of the model affect desired MOEs.

The analysis in chapter 4 identified a statistically significant increase in the replication generation time for control variates. This difference in time ranges between 0.01 and 0.18 second. The size of the difference is a fraction of a second and is not

practically significant. Also, the model R^2 s are small and the reduction in the halfwidths are small, but the effects of the reduction may be significant to the analysis. Therefore, consistent use of control variates is practical and effective in light of the drawbacks.

5.1.2. Common Random Numbers.

When comparing different configurations of a system, a form of common random numbers is generally used, either voluntarily or nonvoluntarily. When two or more configurations start with the same seeds and only one stream is accessed, common random numbers are used. This could potentially cause unintentional problems. Since common random numbers are most likely being used, they should be used properly where all of the random inputs are synchronized.

In this research, common random numbers did not necessarily reduce all of the halfwidths. In the 19 MOEs analyzed, there were 14 halfwidth reductions and 5 halfwidth increases. When looking through the changes in the halfwidths, the largest reduction is 16.25% with a total of 7 MOEs with reductions greater than 7%, while the largest increase in the halfwidths was 6.03%. Therefore, it is more likely to get a reduction in a halfwidth than getting an increase in a halfwidth. Also, the size of a reduction in a halfwidth is generally larger than an increase in a halfwidth.

5.1.3. Antithetic Variates.

When looking at the results from antithetic variates, the implementation does not seem very promising. The amount of extra effort in generating the antithetic pair runs results in only 11 of the 19 MOEs analyzed, 57.89%, receiving a reduction in the halfwidth.

5.1.4. Control Variates and Antithetic Variates.

This method is a little more promising than the standard antithetic variates. It still requires the same amount of effort in generating the antithetic pair runs and only 57.89% of the MOEs analyzed received a reduction in the halfwidths. The major difference is that the 11 reductions in halfwidths are larger than either antithetic variates or control variates independently. Also the 8 increases in halfwidths are smaller than the regular antithetic variates. This implies that there still may be some benefit in using this method if the MOE is determined to be reducible by antithetic variates. Also, since control variates are applied in this method, insight gained from analyzing the weight and direction of the controls can be beneficial.

5.1.5. Control Variates and Common Random Numbers.

This method did not prove very successful. Thirteen of the 19 or 68% of the MOEs received a reduction in variance, and the decision changed 3 times. The CRN method has produced mixed results in the past, so an application of just the CVs was examined. The analysis of the CV by itself did prove successful, 18 of the 19 or 95% of MOEs received a reduction in the halfwidth. Therefore, some sort of application of only the CV method may be beneficial to implement in two system comparisons.

5.1.6. Random Number Generator.

To properly implement common random numbers, a new random number generator needed to be implemented. With the implementation of a new random number generator, we needed to make sure the new random number generator would not significantly alter the THUNDER results. Three different comparisons were performed. They were the new random number generator without synchronizing all random inputs

against the original random number generator, the new random number generator synchronizing all random inputs against the original random number generator, and the new random number generator without synchronizing all random inputs against the new random number generator synchronizing all random inputs. The results for all three analyses were the same. At an $\alpha = 0.05$ level, all MOEs were statistically equal. An important part of the test is that the replication times were also statistically equal.

5.2. Recommendations for Further Work or Study

While working on this research and examining the THUNDER source code some topics for further work or study were discovered. Some of them are small fixes and some are areas where an analysis is needed.

5.2.1. Further THUNDER Work.

First, examination of the random variate modules of THUNDER, it was realized that THUNDER does not allow the analyst to assign all three parameters to the triangular distribution. Fixing this problem would require a through search through the code to identify all sections of code that are associated with the triangular distribution.

Second, more random variate distributions should be added to THUNDER. Currently THUNDER only allows the 13 distributions in Table 3.2. More distributions would allow more flexibility for the analyst.

Third, incorporate control variates and antithetic variates into the post processors. Application should be simple, by following the methodology used in this research. An output of control variate weights should also be incorporated into the post processors. Common random numbers does not need to be added to a postprocessor since it is a passive variance reduction technique.

Fourth, a table identifying the random inputs and what they are used for should be made for THUNDER users. This could be added as an appendix to the THUNDER documentation and used in conjunction to control variate weights after it is incorporated in a post processor.

Fifth, some of the random inputs in THUNDER are mislabeled. While using the name structure to locate the random inputs, the are **..BSE030.1**, **..BSE001.1**, **..BSE001.2**, and **..AIR007.1** were not in the proper source files. After a thorough search through every source files, the correct source files were identified. Therefore, they should be changed to **..UTL260.1**, **..BSE225.1**, **..BSE225.2**, and **..AIR014.1** respectively.

Sixth, permanently implement a new random number generator in THUNDER. The random number generator used for this research is authorized for student use and authorization from Dr. L'Ecuyer is needed to implement MRG32k3a for commercial purposes. It is also possible, with a little research, that any of the other parameters from Dr. L'Ecuyers article (16) could be used to build a combined multiple recursive random number generator for the Air Force.

5.2.2. Further THUNDER Study.

First, find a way to utilize random inputs that use more than one distribution. These variates are not used in the current analysis. A possible direction to go from here is to apply control variates at the central random number draw and not on the random inputs.

Second, test control variates, common random numbers, and antithetic variates with larger THUNDER databases. The ME database is relatively small and this may affect the response of the variance reduction technique. Also, a test to see if test pilot

runs of a small amount of days or only a couple of replications has the same affect as a full test with a large amount of days or replications.

Third, try applying antithetic variates only to random inputs that are not branches and common random numbers to branches. This method may make antithetic variates more effective. Then, combined with control variates, this method may have a lot of variance reduction potential.

THUNDER 6.808: ME

C O M B A T C Y C L E

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TIME: 1:1200
 R E P O R T
 FLOT MOVEMENT
 REPORT: CC-4
 PART 1

---OPPOSING CMD---		SQ. MILES		WIDTH		-----FLOT SEGMENT-----							
ID	COMMAND	NAME	GAINED (LOST)	MILES	MILES	ID	NAME	LATITUDE	LONGITUDE	FROM	LATITUDE	LONGITUDE	TO
1013	PERSIAN GU		0	118		2009	PERSIAN GU	27D43.0M-N	52D15.1M-E		28D50.9M-N	50D46.0M-E	
1008	PERSIAN GU		0	118		2010	PERSIAN GU	28D50.9M-N	50D46.0M-E		28D34.6M-N	48D19.9M-E	
1009	MARINES		401	62		2011	1 IRAQI AR	28D34.6M-N	48D19.9M-E		29D06.8M-N	47D30.0M-E	
1010	ARAB CORPS		391	50		2012	2 IRAQI AR	29D06.8M-N	47D30.0M-E		29D14.8M-N	46D38.6M-E	
1020	VII CORPS		1087	75		2013	3 IRAQI AR	29D14.8M-N	46D38.6M-E		29D44.9M-N	45D32.8M-E	
1021	XVIII AIRB		1767	121		2016	BAGHDAD FO	29D44.9M-N	45D32.8M-E		29D50.4M-N	43D50.5M-E	
1012	DESERT FOR		0	109		2014	DESERT FOR	29D50.4M-N	43D50.5M-E		30D09.0M-N	42D30.2M-E	
1014	DESERT FOR		0	109		2015	DESERT FOR	30D09.0M-N	42D30.2M-E		31D02.0M-N	42D16.3M-E	
1015	DESERT FOR		0	109		2017	DESERT FOR	31D02.0M-N	42D16.3M-E		31D48.9M-N	40D33.2M-E	
											31D50.5M-N	40D23.5M-E	
											32D32.0M-N	38D43.4M-E	

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FLOT

INDEX	WIDTH	FORCE	LONGITUDE	BLUE UNIT	(FEET)	RATIO	RED UNIT	FRACTION	ID	NAME	FRACTION	ID	NAME	FRACTION
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2	28D50.9M-N	50D46.0M-E	623363	1.000	1034 PG	1.000	2045 PG FORCE	1.000	2045	PG FORCE	1.000	2045	PG FORCE	1.000
3	28D34.6M-N	48D19.9M-E	63881	2.826	1101 1 SAUDI DI	.467	2101 1 1 ID	1.000	2101	1 1 ID	1.000	2101	1 1 ID	1.000
4	28D37.3M-N	48D07.8M-E	66801	2.635	1101 1 SAUDI DI	.489	2102 1 2 ID	1.000	2102	1 2 ID	1.000	2102	1 2 ID	1.000
5	28D39.0M-N	47D54.5M-E	5974	2.639	1101 1 SAUDI DI	.044	2103 1 3 ID	.092	2103	1 3 ID	.092	2103	1 3 ID	.092
6	28D39.2M-N	47D53.4M-E	58825	2.775	1102 1 MARINE E	.616	2103 1 3 ID	.908	2103	1 3 ID	.908	2103	1 3 ID	.908
7	28D40.9M-N	47D41.8M-E	36699	2.797	1102 1 MARINE E	.384	2104 1 4 ID	.544	2104	1 4 ID	.544	2104	1 4 ID	.544
8	28D46.7M-N	47D37.7M-E	30801	2.786	1103 2 MARINE E	.321	2104 1 4 ID	.456	2104	1 4 ID	.456	2104	1 4 ID	.456
9	28D55.1M-N	47D36.5M-E	65102	2.771	1103 2 MARINE E	.679	2105 1 5 ID	1.000	2105	1 5 ID	1.000	2105	1 5 ID	1.000
10	29D06.8M-N	47D30.0M-E	47287	3.767	1201 3RD EGYPTI	.486	2201 2 1 ID	1.000	2201	2 1 ID	1.000	2201	2 1 ID	1.000
11	29D07.7M-N	47D20.4M-E	50036	4.985	1201 3RD EGYPTI	.514	2202 2 2 ID	.773	2202	2 2 ID	.773	2202	2 2 ID	.773
12	29D08.7M-N	47D10.2M-E	14678	5.011	1202 4TH EGYPTI	.150	2202 2 2 ID	.227	2202	2 2 ID	.227	2202	2 2 ID	.227
13	29D10.5M-N	47D08.2M-E	46112	3.786	1202 4TH EGYPTI	.473	2203 2 3 ID	1.000	2203	2 3 ID	1.000	2203	2 3 ID	1.000
14	29D11.5M-N	46D58.9M-E	36804	5.006	1202 4TH EGYPTI	.377	2204 2 4 ID	.629	2204	2 4 ID	.629	2204	2 4 ID	.629
15	29D12.3M-N	46D51.5M-E	21745	5.663	1203 9TH SYRIAN	.322	2204 2 4 ID	.371	2204	2 4 ID	.371	2204	2 4 ID	.371
16	29D14.1M-N	46D48.0M-E	45804	4.283	1203 9TH SYRIAN	.678	2205 2 5 ID	1.000	2205	2 5 ID	1.000	2205	2 5 ID	1.000
17	29D14.8M-N	46D38.6M-E	73323	7.055	1301 1 UK ARM D	.844	2301 3 1 ID	1.000	2301	3 1 ID	1.000	2301	3 1 ID	1.000
18	29D20.7M-N	46D26.5M-E	13520	10.059	1301 1 UK ARM D	.156	2302 3 2 ID	.161	2302	3 2 ID	.161	2302	3 2 ID	.161
19	29D20.7M-N	46D23.6M-E	70354	10.064	1302 1 US ARM D	.806	2302 3 2 ID	.839	2302	3 2 ID	.839	2302	3 2 ID	.839
20	29D26.3M-N	46D12.0M-E	16978	7.951	1302 1 US ARM D	.194	2303 3 3 ID	.239	2303	3 3 ID	.239	2303	3 3 ID	.239
21	29D27.6M-N	46D09.2M-E	54065	7.934	1303 2 US CAV R	.938	2303 3 3 ID	.761	2303	3 3 ID	.761	2303	3 3 ID	.761
22	29D31.9M-N	46D00.3M-E	3602	7.024	1303 2 US CAV R	.062	2304 3 4 ID	.037	2304	3 4 ID	.037	2304	3 4 ID	.037
23	29D32.2M-N	45D59.7M-E	87116	7.062	1304 3 US ARM D	1.000	2304 3 4 ID	.898	2304	3 4 ID	.898	2304	3 4 ID	.898
24	29D39.2M-N	45D45.3M-E	6299	7.029	1305 1 US INF D	.084	2304 3 4 ID	.065	2304	3 4 ID	.065	2304	3 4 ID	.065
25	29D39.7M-N	45D44.2M-E	68438	7.029	1305 1 US INF D	.916	2305 3 5 ID	1.000	2305	3 5 ID	1.000	2305	3 5 ID	1.000
26	29D44.9M-N	45D32.8M-E	140417	+E+009	1401 24 US MECH	1.000	2040 DESERT FOR	.285	2040	DESERT FOR	.285	2040	DESERT FOR	.285
27	29D23.4M-N	44D49.2M-E	162874	+E+009	1402 1ST US CAV	1.000	2040 DESERT FOR	.331	2040	DESERT FOR	.331	2040	DESERT FOR	.331
28	29D35.8M-N	44D22.0M-E	105203	+E+009	1403 3RD US CAV	1.000	2040 DESERT FOR	.214	2040	DESERT FOR	.214	2040	DESERT FOR	.214
29	29D43.9M-N	44D04.5M-E	45518	+E+009	1404 101ST US A	1.000	2040 DESERT FOR	.092	2040	DESERT FOR	.092	2040	DESERT FOR	.092
30	29D47.5M-N	43D56.9M-E	38114	+E+009	1405 82ND US AI	.843	2040 DESERT FOR	.077	2040	DESERT FOR	.077	2040	DESERT FOR	.077
31	29D50.4M-N	43D50.5M-E	7093	+E+009	1405 82ND US AI	.157	2035 DESERT FOR	.011	2035	DESERT FOR	.011	2035	DESERT FOR	.011
32	29D46.0M-N	43D46.3M-E	140545	+E+009	1406 6TH FR LIG	1.000	2035 DESERT FOR	.220	2035	DESERT FOR	.220	2035	DESERT FOR	.220
33	30D09.0M-N	43D30.2M-E	492126	1.000	1043 DESERT FOR	.857	2035 DESERT FOR	.769	2035	DESERT FOR	.769	2035	DESERT FOR	.769
34	31D02.0M-N	42D16.3M-E	82021	1.000	1043 DESERT FOR	.143	2036 DESERT FOR	.135	2036	DESERT FOR	.135	2036	DESERT FOR	.135
35	31D09.0M-N	42D02.8M-E	524934	1.000	1044 DESERT FOR	.914	2036 DESERT FOR	.865	2036	DESERT FOR	.865	2036	DESERT FOR	.865
36	31D48.9M-N	40D33.2M-E	49213	1.000	1044 DESERT FOR	.086	2037 DESERT FOR	.079	2037	DESERT FOR	.079	2037	DESERT FOR	.079
37	31D50.5M-N	40D23.5M-E	574147	1.000	1045 DESERT FOR	1.000	2037 DESERT FOR	.921	2037	DESERT FOR	.921	2037	DESERT FOR	.921

THUNDER 6.808: ME

C O M B A T C Y C L E

TIME: 1:1200

R E P O R T

REPORT: CC-4

FLOT MOVEMENT

PART 1

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---OPPOSING CMD---		SQ. MILES		WIDTH		FLOT SEGMENT		FROM		TO	
ID	NAME	GAINED (LOST)	MILES	MILES	MILES	ID	NAME	LATITUDE	LONGITUDE	LATITUDE	LONGITUDE
2009	PERSIAN GU	0	118			1013	PERSIAN GU	27D43.0M-N	52D15.1M-E	28D50.9M-N	50D46.0M-E
2010	PERSIAN GU	0	118			1008	PERSIAN GU	28D50.9M-N	50D46.0M-E	28D34.6M-N	48D19.9M-E
2011	1 IRAQI AR	(401)	62			1009	MARINES	28D34.6M-N	48D19.9M-E	29D06.8M-N	47D30.0M-E
2012	2 IRAQI AR	(391)	50			1010	ARAB CORPS	29D06.8M-N	47D30.0M-E	29D14.8M-N	46D38.6M-E
2013	3 IRAQI AR	(1087)	75			1020	VII CORPS	29D14.8M-N	46D38.6M-E	29D44.9M-N	45D32.8M-E
2016	BAGHDAD FO	(1359)	93			1021	XVIII AIRB	29D44.9M-N	45D32.8M-E	29D50.4M-N	43D50.5M-E
2014	DESERT FOR	(408)	121			1021	XVIII AIRB	29D50.4M-N	43D50.5M-E	30D09.0M-N	43D30.2M-E
2015	DESERT FOR	0	115			1012	DESERT FOR	30D09.0M-N	43D30.2M-E	31D02.0M-N	42D16.3M-E
2017	DESERT FOR	0	118			1014	DESERT FOR	31D09.0M-N	42D16.3M-E	31D48.9M-N	40D33.2M-E
						1015	DESERT FOR	31D48.9M-N	40D33.2M-E	31D50.5M-N	40D23.5M-E
								31D50.5M-N	40D23.5M-E	32D32.0M-N	38D43.4M-E

THUNDER 6.808: ME

C O M B A T C Y C L E

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 FLOT MOVEMENT
 REPORT: CC-4
 PART 1

---OPPOSING CMD---		SQ. MILES		WIDTH		FLOT SEGMENT		FROM		TO	
ID	COMMAND	GAINED	(LOST)	MILES	MILES	ID	NAME	LATITUDE	LONGITUDE	LATITUDE	LONGITUDE
1013	PERSIAN GU	0	0	118		2009	PERSIAN GU	27D43.0M-N	52D15.1M-E	28D50.9M-N	50D46.0M-E
1008	PERSIAN GU	0	0	118		2010	PERSIAN GU	28D50.9M-N	50D46.0M-E	28D34.6M-N	48D19.9M-E
1009	MARINES	0	0	62		2011	1 IRAQI AR	28D34.6M-N	48D19.9M-E	29D12.3M-N	47D33.6M-E
1010	ARAB CORPS	384	0	50		2012	2 IRAQI AR	29D12.3M-N	47D33.6M-E	29D25.5M-N	46D45.4M-E
1020	VII CORPS	1043	0	75		2013	3 IRAQI AR	29D25.5M-N	46D45.4M-E	29D55.5M-N	45D39.5M-E
1021	XVIII AIRB	1701	0	121		2016	BAGHDAD FO	29D55.5M-N	45D39.5M-E	30D00.4M-N	43D56.6M-E
1012	DESERT FOR	0	0	109		2014	DESERT FOR	30D00.4M-N	43D56.6M-E	30D09.0M-N	43D30.2M-E
1014	DESERT FOR	0	0	109		2015	DESERT FOR	30D09.0M-N	43D30.2M-E	31D02.0M-N	42D16.3M-E
1015	DESERT FOR	0	0	109		2017	DESERT FOR	31D09.0M-N	42D16.3M-E	31D48.9M-N	40D33.2M-E
						2017	DESERT FOR	31D50.5M-N	40D33.2M-E	32D32.0M-N	38D43.4M-E

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WIDTH INDEX	FORCE LATITUDE	LONGITUDE	BLUE UNIT (FEET)	RATIO	RED UNIT (FEET)	NAME	FRACTION	ID	NAME	FRACTION
1	27D43.0M-N	52D15.1M-E	623360	1.000	1032 PG	1032 PG	1.000	2047 PG FORCE	2047 PG FORCE	1.000
2	28D50.9M-N	50D46.0M-E	623360	1.000	1034 PG	1034 PG	1.000	2045 PG FORCE	2045 PG FORCE	1.000
3	28D34.6M-N	48D19.9M-E	63346	3.498	1101 1 SAUDI DI	1101 1 SAUDI DI	.560	2101 1 1 ID	2101 1 1 ID	1.000
4	28D37.3M-N	48D07.9M-E	49695	3.261	1101 1 SAUDI DI	1101 1 SAUDI DI	.440	2102 1 2 ID	2102 1 2 ID	.730
5	28D41.1M-N	47D59.7M-E	18425	2.881	1102 1 MARINE E	1102 1 MARINE E	.144	2102 1 2 ID	2102 1 2 ID	.270
6	28D38.7M-N	47D54.2M-E	66329	2.885	1102 1 MARINE E	1102 1 MARINE E	.520	2103 1 3 ID	2103 1 3 ID	1.000
7	28D41.6M-N	47D41.8M-E	42802	2.905	1102 1 MARINE E	1102 1 MARINE E	.336	2104 1 4 ID	2104 1 4 ID	.639
8	28D47.8M-N	47D36.6M-E	24226	4.137	1103 2 MARINE E	1103 2 MARINE E	.277	2104 1 4 ID	2104 1 4 ID	.361
9	28D55.2M-N	47D36.2M-E	63264	4.146	1103 2 MARINE E	1103 2 MARINE E	.723	2105 1 5 ID	2105 1 5 ID	1.000
10	29D12.3M-N	47D33.6M-E	43051	3.695	1201 3RD EGYPTI	1201 3RD EGYPTI	.441	2201 2 1 ID	2201 2 1 ID	1.000
11	29D14.9M-N	47D26.0M-E	54639	4.128	1201 3RD EGYPTI	1201 3RD EGYPTI	.559	2202 2 2 ID	2202 2 2 ID	.982
12	29D16.2M-N	47D15.0M-E	981	4.148	1202 4TH EGYPTI	1202 4TH EGYPTI	.014	2202 2 2 ID	2202 2 2 ID	.018
13	29D15.8M-N	47D14.5M-E	53514	3.953	1202 4TH EGYPTI	1202 4TH EGYPTI	.780	2203 2 3 ID	2203 2 3 ID	1.000
14	29D17.2M-N	47D03.9M-E	14091	4.167	1202 4TH EGYPTI	1202 4TH EGYPTI	.205	2204 2 4 ID	2204 2 4 ID	.246
15	29D15.5M-N	46D59.8M-E	43104	4.193	1203 9TH SYRIAN	1203 9TH SYRIAN	.448	2204 2 4 ID	2204 2 4 ID	.754
16	29D19.1M-N	46D52.8M-E	53087	3.640	1203 9TH SYRIAN	1203 9TH SYRIAN	.552	2205 2 5 ID	2205 2 5 ID	1.000
17	29D25.5M-N	46D45.4M-E	71007	10.718	1301 1 UK ARM D	1301 1 UK ARM D	.819	2301 3 1 ID	2301 3 1 ID	1.000
18	29D31.2M-N	46D33.7M-E	15643	11.573	1301 1 UK ARM D	1301 1 UK ARM D	.181	2302 3 2 ID	2302 3 2 ID	.285
19	29D31.3M-N	46D30.4M-E	39311	11.601	1302 1 US ARM D	1302 1 US ARM D	.446	2302 3 2 ID	2302 3 2 ID	.715
20	29D34.4M-N	46D23.9M-E	48743	11.584	1302 1 US ARM D	1302 1 US ARM D	.554	2303 3 3 ID	2303 3 3 ID	.637
21	29D38.3M-N	46D15.9M-E	27825	11.594	1303 2 US CAV R	1303 2 US CAV R	.486	2303 3 3 ID	2303 3 3 ID	.363
22	29D40.5M-N	46D11.3M-E	29396	11.594	1303 2 US CAV R	1303 2 US CAV R	.514	2304 3 4 ID	2304 3 4 ID	.305
23	29D42.9M-N	46D06.4M-E	67080	11.588	1304 3 US ARM D	1304 3 US ARM D	.769	2304 3 4 ID	2304 3 4 ID	.695
24	29D48.2M-N	45D55.3M-E	20131	11.588	1304 3 US ARM D	1304 3 US ARM D	.231	2305 3 5 ID	2305 3 5 ID	.213
25	29D49.8M-N	45D52.0M-E	74560	11.594	1305 1 US INF D	1305 1 US INF D	1.000	2305 3 5 ID	2305 3 5 ID	.787
26	29D55.5M-N	45D39.5M-E	140709	18.054	1401 24 US MECH	1401 24 US MECH	1.000	2402 4 2 ID	2402 4 2 ID	.286
27	29D34.1M-N	44D55.8M-E	163182	18.335	1402 1ST US CAV	1402 1ST US CAV	1.000	2402 4 2 ID	2402 4 2 ID	.332
28	29D46.6M-N	44D28.5M-E	105807	18.349	1403 3RD US CAV	1403 3RD US CAV	1.000	2402 4 2 ID	2402 4 2 ID	.215
29	29D54.8M-N	44D10.9M-E	45630	18.314	1404 101ST US A	1404 101ST US A	1.000	2402 4 2 ID	2402 4 2 ID	.093
30	29D58.4M-N	44D03.2M-E	36798	18.177	1405 82ND US AI	1405 82ND US AI	.811	2402 4 2 ID	2402 4 2 ID	.075
31	30D00.4M-N	43D56.6M-E	8550	+E+009	1405 82ND US AI	1405 82ND US AI	.189	2035 DESERT FOR	2035 DESERT FOR	.013
32	29D56.9M-N	43D52.6M-E	139088	+E+009	1406 6TH FR LIG	1406 6TH FR LIG	1.000	2035 DESERT FOR	2035 DESERT FOR	.217
33	30D09.0M-N	43D30.2M-E	492126	1.000	1043 DESERT FOR	1043 DESERT FOR	.857	2035 DESERT FOR	2035 DESERT FOR	.769
34	31D02.0M-N	42D16.3M-E	82021	1.000	1043 DESERT FOR	1043 DESERT FOR	.143	2036 DESERT FOR	2036 DESERT FOR	.135
35	31D09.0M-N	42D02.8M-E	524934	1.000	1044 DESERT FOR	1044 DESERT FOR	.914	2036 DESERT FOR	2036 DESERT FOR	.865
36	31D48.9M-N	40D33.2M-E	49213	1.000	1044 DESERT FOR	1044 DESERT FOR	.086	2037 DESERT FOR	2037 DESERT FOR	.079
37	31D50.5M-N	40D23.5M-E	574147	1.000	1045 DESERT FOR	1045 DESERT FOR	1.000	2037 DESERT FOR	2037 DESERT FOR	.921

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* RED *
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---OPPOSING CMD--- FLOT SEGMENT-----

ID	COMMAND	NAME	GAINED	LOST	SQ. MILES	WIDTH	FROM	TO
			MILES	MILES		MILES	LATITUDE	LONGITUDE
2009	PERSIAN GU	PERSIAN GU	0	0	118	118	28D50.9M-N	50D46.0M-E
2010	PERSIAN GU	PERSIAN GU	0	0	118	118	28D34.6M-N	48D19.9M-E
2011	1 IRAQI AR	MARINES	0	0	62	62	29D12.3M-N	47D33.6M-E
2012	2 IRAQI AR	ARAB CORPS	(384)	(384)	50	50	29D25.5M-N	46D45.4M-E
2013	3 IRAQI AR	VII CORPS	(1043)	(1043)	75	75	29D55.5M-N	45D39.5M-E
2016	BAGHDAD FO	XVIII AIRB	(1309)	(1309)	93	93	30D00.4M-N	43D56.6M-E
2014	DESERT FOR	XVIII AIRB	(392)	(392)	121	121	30D09.0M-N	43D30.2M-E
2015	DESERT FOR	DESERT FOR	0	0	115	115	31D02.0M-N	42D16.3M-E
2017	DESERT FOR	DESERT FOR	0	0	118	118	31D09.0M-N	42D02.8M-E
		DESERT FOR					31D48.9M-N	40D33.2M-E
		DESERT FOR					31D50.5M-N	40D23.5M-E
		DESERT FOR					32D32.0M-N	38D43.4M-E

THUNDER 6.808: ME

11/08/2004 08:55 PAGE 1

AIRCRAFT LOSSES
SUMMARY REPORT

TIME: 1:0000
REPORT: AW-3

ID	TYPE AIRCRAFT	PERCENT	LOSSES	SORTIES LOST		NUMBER OF SORTIES	AIRCRAFT			CURRENT CYCLE	START	GAIN	END
				TO AIR	AIR SURFACE		TOTAL	OTHER	CUMULATIVE				
1001	A-10		268	0	0	0	0	0	0	72	0	72	
1002	F-16		184	2	2	0	4	2	2	96	0	92	
1003	RF-4		52	0	2	0	2	4	4	24	0	22	
1004	F-111		391	8	4	0	12	3	3	204	0	192	
1005	F-15		372	4	1	0	5	1	1	192	0	187	
1006	AV-8B		132	0	0	0	0	0	0	60	0	60	
1007	F/A-18		150	0	0	0	0	0	0	108	0	108	
1008	A-6		155	1	0	0	1	1	1	118	0	117	
1009	F-14		130	0	0	0	0	0	0	60	0	60	
1010	E-3		6	0	0	0	0	0	0	12	0	12	
1011	E-8		4	0	0	0	0	0	0	6	0	6	
1012	KC-135		58	0	0	0	0	0	0	72	0	72	
1013	C-17		4	0	0	0	0	0	0	40	0	40	
1014	C-130H		0	0	0	0	0	0	0	56	0	56	
1099	ABL		22	0	1	0	1	5	5	24	0	23	
1928		15	10	0	25	0	1144	0	1119				

A I R C R A F T L O S S
S U M M A R Y R E P O R T

TIME: 1:0000
REPORT: AW-3

* RED *
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ID	TYPE AIRCRAFT	NAME	LOSSES		SORTIES LOST		AIRCRAFT			START	GAIN	END
			PERCENT	NUMBER OF SORTIES	TO AIR	AIR SURFACE	TOTAL	CURRENT	CUMULATIVE			
2001	MIG-23		80	18	0	0	0	18	23	100	0	82
2002	MIRAGE F-1		264	61	5	0	0	66	25	125	0	59
2003	MIG-21		72	18	0	0	0	18	25	150	0	132
2004	MIG-29		70	15	0	0	0	15	21	25	0	10
2005	SU-25		104	0	5	0	0	5	5	50	0	45
2006	MAINSTAY		3	0	0	0	0	0	0	4	0	4
2099	SCUD		59	5	0	1	0	6	10	128	0	68
=====	117	10	1	0	128	=====	=====	582	0	400	=====	=====

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TIME: 1:0000
 - 2:0000
 REPORT: AW-5

PART 1

NUMBER OF SORTIES PLANNED / NUMBER OF SORTIES FLOWN

AIR BASE

SQUADRON	DCA	ODCA	HVAA	BARCAP	FSWP	AIRESC	STI	CAS	BAI	INT	OCA	OTBM	DTBM	DSEAD	SSUP
RIYADH - 1001	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
AWACS 10301	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
JSTARS 10801	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
AAAR 3 11020	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
DHAHRAN - 1002	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	40/28	8/6	0/0	0/0	0/0	0/0
A6E US 10604	0/0	0/0	0/0	12/6	0/0	0/0	0/0	0/0	0/0	64/36	0/0	0/0	0/0	0/0	30/18
FA18 U 11804	0/0	0/0	0/0	0/0	0/0	0/0	0/0	196/118	44/14	0/0	0/0	0/0	0/0	0/0	0/0
AV8B U 10804	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
AAAR 1 11018	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	12/6	0/0	0/0	0/0	196/118	44/14	104/64	8/6	0/0	0/0	0/0	30/18
JIDDAH - 1003	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
AAAR 2 11019	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
C-130/ 11022	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
MEDINA - 1004	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
EF111 11109	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
AL JAWF - 1005	0/0	0/0	0/0	8/8	0/0	0/0	0/0	0/0	0/0	76/44	0/0	0/0	0/0	0/0	0/0
F16 3 11603	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
C-17/1 11021	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	8/8	0/0	0/0	0/0	0/0	0/0	76/44	0/0	0/0	0/0	0/0	0/0
RAFHA - 1006	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
AT TA'IF - 1007	0/0	0/0	0/0	0/0	0/0	0/0	10/10	0/0	0/0	38/38	0/0	0/0	0/0	0/0	0/0
F117 1 11104	0/0	0/0	0/0	0/0	0/0	0/0	10/10	0/0	0/0	38/38	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	10/10	0/0	0/0	38/38	0/0	0/0	0/0	0/0	0/0
AL QAYSUMAN - 1010	0/0	0/0	0/0	0/0	0/0	0/0	0/0	96/96	0/0	0/0	0/0	0/0	0/0	0/0	0/0
A10 1 11001	0/0	0/0	0/0	0/0	0/0	0/0	0/0	96/96	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	96/96	0/0	0/0	0/0	0/0	0/0	0/0	0/0
ARAR - 1011	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0

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TIME: 1:0000
 - 2:0000
 REPORT: AW-5

PART 1

NUMBER OF SORTIES PLANNED / NUMBER OF SORTIES FLOWN

AIR BASE

NAME ID	DCA	ODCA	HVAA	BARCAP	FSWP	AIRESC	STI	CAS	BAI	INT	OCA	OTBM	DTBM	DSEAD	SSUP
DUBAI - 1012															
TOTAL	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
CV 1 - 1013															
F14 US 11401	6/ 4	30/ 12	0/ 0	24/ 24	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
A6E US 10601	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	50/ 50	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
FA18 U 11801	72/ 20	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
EA6B U 19601	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL	78/ 24	30/ 12	0/ 0	24/ 24	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	50/ 50	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
CV 2 - 1014															
F14 US 11402	2/ 0	0/ 0	0/ 0	10/ 10	24/ 22	24/ 18	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
A6E US 10602	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	49/ 49	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
FA18 U 11802	8/ 0	44/ 12	0/ 0	20/ 20	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
EA6B U 19602	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL	10/ 0	44/ 12	0/ 0	30/ 30	24/ 22	24/ 18	0/ 0	0/ 0	0/ 0	49/ 49	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
CV 3 - 1015															
F14 US 11403	16/ 0	0/ 0	0/ 0	44/ 40	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
A6E US 10603	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
FA18 U 11803	40/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
EA6B U 19603	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL	56/ 0	0/ 0	0/ 0	44/ 40	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
KING KHALID MIL CITY - 1016															
TORN I 11105	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	47/ 47	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TORN I 11108	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	48/ 48	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
F15 3 11503	6/ 0	0/ 0	0/ 0	8/ 8	36/ 36	20/ 20	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL	6/ 0	0/ 0	0/ 0	8/ 8	36/ 36	20/ 20	0/ 0	0/ 0	0/ 0	95/ 95	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
BAHRAIN INTL - 1017															
C-130/ 11023	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
AL AHSA - 1018															
TORN I 11106	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	48/ 48	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TORN A 11507	24/ 12	0/ 0	0/ 0	46/ 46	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL	24/ 12	0/ 0	0/ 0	46/ 46	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	48/ 48	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
AL KHARJ - 1019															
C-130/ 11024	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0

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TIME: 1:0000
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 REPORT: AW-5

PART 1

NUMBER OF SORTIES PLANNED / NUMBER OF SORTIES FLOWN

AIR BASE

NAME ID

SQUADRON

	DCA	ODCA	HVAA	BARCAP	FSWP	AIRESC	STI	CAS	BAI	INT	OCA	OTBM	DTBM	DSEAD	SSUP
KING KHALID INTL - 1020															
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
THUMAMAH - 1021															
TORN I 11107	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	48/48	0/0	0/0	0/0	0/0	0/0
F15 1 11501	6/0	0/0	0/0	8/8	56/56	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
ABL 2 11510	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	16/16	0/0	0/0
TOTAL	6/0	0/0	0/0	8/8	56/56	0/0	0/0	0/0	0/0	48/48	0/0	0/0	16/16	0/0	0/0
HAFR AL BATIN - 1022															
A10 3 11003	0/0	0/0	0/0	0/0	0/0	0/0	0/0	56/44	40/32	0/0	0/0	0/0	0/0	0/0	0/0
F16 2 11602	44/28	0/0	0/0	40/36	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
F15 4 11504	14/0	0/0	0/0	0/0	0/0	56/42	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	58/28	0/0	0/0	40/36	0/0	56/42	0/0	56/44	40/32	0/0	0/0	0/0	0/0	0/0	0/0
GASSIM - 1023															
RF4 1 10401	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
F15 2 11502	36/8	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
ABL 1 11509	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	6/6	0/0	0/0
TOTAL	36/8	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	6/6	0/0	0/0
DOHA INTL - 1024															
TORN A 11508	70/16	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	70/16	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
RAS MISHAB - 1025															
A10 2 11002	0/0	0/0	0/0	0/0	0/0	0/0	0/0	96/96	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	96/96	0/0	0/0	0/0	0/0	0/0	0/0	0/0
HAIL - 1026															
F16 1 11601	84/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
WEASEL 11604	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	6/0	46/40
TOTAL	84/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	6/0	46/40
YENBO - 1027															
F111 2 11102	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	20/20	0/0	0/0	28/26	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	20/20	0/0	0/0	28/26	0/0	0/0
WEJH - 1028															
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0

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TIME: 1:0000
 - 2:0000
 REPORT: AW-5

PART 1

NUMBER OF SORTIES PLANNED / NUMBER OF SORTIES FLOWN

AIR BASE

NAME ID	SQUADRON	DCA	ODCA	HVAA	BARCAP	FSWP	AIRESC	STI	CAS	BAI	INT	OCA	OTBM	DTBM	DSEAD	SSUP
KING FAISAL AB - 1029																
F111 1	11101	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	48/35	0/0	0/0	0/0
F15 5	11505	0/0	0/0	0/0	20/20	0/0	50/46	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL		0/0	0/0	0/0	20/20	0/0	50/46	0/0	0/0	0/0	0/0	0/0	48/35	0/0	0/0	0/0
AL BIR - 1030																
F15 6	11506	2/0	0/0	0/0	68/54	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL		2/0	0/0	0/0	68/54	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TURAIF - 1031																
TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
GURIAT - 1032																
TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
GIZAN - 1033																
TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
SHARURAH - 1034																
TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
ABHA - 1035																
TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
KHANIS MUSHAIT - 1036																
TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
BISHA - 1037																
TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
SULAYEL - 1038																
TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
KING ABDUL AZIZ - 1039																
F15E 1	11103	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	47/47	0/0	0/0	0/0	0/0	0/0
TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	47/47	0/0	0/0	0/0	0/0	0/0

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TIME: 1:0000
 - 2:0000
 REPORT: AW-5
 PART 2

NUMBER OF SORTIES PLANNED / NUMBER OF SORTIES FLOWN

AIR BASE	NAME ID	SQUADRON	CSUP	ESCSUP	SJAM	CJAM	ESCJAM	RECCE	SREC	AEW	AAR	LIFT	XXXX	RESERVE	DISPERS	TOTAL
RIYADH - 1001																
A6E US	10604		0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	8/ 6	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	8/ 6
AWACS	10301		0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	4/ 4
JSTARS	10801		0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	45/ 37	0/ 0	0/ 0	0/ 0	0/ 0	45/ 37
AAR 3	11020		0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	8/ 6	45/ 37	0/ 0	0/ 0	0/ 0	0/ 0	57/ 47
TOTAL			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
DHAHRAN - 1002																
A6E US	10604		0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
FA18 U	11804		0/ 0	66/ 38	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
AV8B U	10804		0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
AAR 1	11018		0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	48/ 11	0/ 0	0/ 0	0/ 0	0/ 0	48/ 11
TOTAL			0/ 0	66/ 38	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
JIDDAH - 1003																
AAR 2	11019		0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	48/ 10	0/ 0	0/ 0	0/ 0	0/ 0	48/ 10
C-130/	11022		0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	4/ 4	0/ 0	0/ 0	0/ 0	4/ 4
TOTAL			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	4/ 4	0/ 0	0/ 0	0/ 0	0/ 0
MEDINA - 1004																
EF111	11109		0/ 0	0/ 0	12/ 12	4/ 4	8/ 8	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL			0/ 0	0/ 0	12/ 12	4/ 4	8/ 8	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
AL JAWF - 1005																
F16 3	11603		0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
C-17/1	11021		0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
RAFHA - 1006																
TOTAL			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
AT TA'IF - 1007																
F117 1	11104		0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
AL QAYSUMAN - 1010																
A10 1	11001		0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
ARAR - 1011																
TOTAL			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0

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TIME: 1:0000
 - 2:0000
 REPORT: AW-5

PART 2

NUMBER OF SORTIES PLANNED / NUMBER OF SORTIES FLOWN

AIR BASE

NAME ID

SQUADRON

	CSUP	ESCSUP	SJAM	CJAM	ESCJAM	RECCE	SREC	AEW	AAR	LIFT	XXXX	RESERVE	DISPERS	TOTAL
DUBAI - 1012	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
CV 1 - 1013														
F14 US 11401	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	60/40
A6E US 10601	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	50/50
FA18 U 11801	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	72/20
EA6B U 19601	0/0	0/0	12/12	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	12/12
TOTAL	0/0	0/0	12/12	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	194/122
CV 2 - 1014														
F14 US 11402	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	60/50
A6E US 10602	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	49/49
FA18 U 11802	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	72/32
EA6B U 19602	0/0	0/0	0/0	4/4	8/6	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	12/10
TOTAL	0/0	0/0	0/0	4/4	8/6	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	193/141
CV 3 - 1015														
F14 US 11403	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	60/40
A6E US 10603	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
FA18 U 11803	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	40/0
EA6B U 19603	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	100/40
KING KHALID MIL CITY - 1016														
TORN I 11105	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	47/47
TORN I 11108	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	48/48
F15 3 11503	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	70/64
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	165/159
BAHRAIN INTL - 1017														
C-130/ 11023	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
AL AHSA - 1018														
TORN I 11106	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	48/48
TORN A 11507	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	70/58
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	118/106
AL KHARJ - 1019														
C-130/ 11024	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0

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TIME: 1:0000
 - 2:0000
 REPORT: AW-5

PART 2

NUMBER OF SORTIES PLANNED / NUMBER OF SORTIES FLOWN

AIR BASE

NAME ID

SQUADRON

	CSUP	ESCSUP	SJAM	CJAM	ESCJAM	RECE	SREC	AEW	AAR	LIFT	XXXX	RESERVE	DISPERS	TOTAL
KING KHALID INTL - 1020														
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
THUMAMAH - 1021														
TORN I 11107	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/48/48
F15 1 11501	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/70/64
ABL 2 11510	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/16/16
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/134/128
HAFR AL BATIN - 1022														
A10 3 11003	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/96/76
F16 2 11602	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/84/64
F15 4 11504	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/70/42
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/250/182
GASSIM - 1023														
RF4 1 10401	0/0	0/0	0/0	0/0	0/0	60/52	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/60/52
F15 2 11502	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/36/8
ABL 1 11509	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/6/6
TOTAL	0/0	0/0	0/0	0/0	0/0	60/52	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/102/66
DOHA INTL - 1024														
TORN A 11508	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/70/16
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/70/16
RAS MISHAB - 1025														
A10 2 11002	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/96/96
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/96/96
HAIL - 1026														
F16 1 11601	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/84/0
WEASEL 11604	8/8	24/20	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/84/68
TOTAL	8/8	24/20	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/168/68
YENBO - 1027														
F11 2 11102	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/48/46
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/48/46
WEJH - 1028														
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0/0

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TIME: 1:0000
 REPORT: AW-5
 PART 2

NUMBER OF SORTIES PLANNED / NUMBER OF SORTIES FLOWN

AIR BASE	NAME ID	CSUP	ESCSUP	SJAM	CJAM	ESCJAM	RECE	SSEC	AEW	AAR	LIFT	XXXX	RESERVE	DISPERS	TOTAL
KING FAISAL AB - 1029															
	F111 1	11101	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	48/35
	F15 5	11505	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	70/66
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	118/101
AL BIR - 1030															
	F15 6	11506	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	70/54
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	70/54
TURAIF - 1031															
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
GURIAT - 1032															
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
GIZAN - 1033															
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
SHARURAH - 1034															
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
ABHA - 1035															
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
KHAMIS MUSHAIT - 1036															
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
BISHA - 1037															
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
SULAYEL - 1038															
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
KING ABDUL AZIZ - 1039															
	F15E 1	11103	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	47/47
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	47/47

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TIME: 1:0000
 - 2:0000
 REPORT: AW-5

PART 1

NUMBER OF SORTIES PLANNED / NUMBER OF SORTIES FLOWN

AIR BASE

NAME ID	DCA	ODCA	HVAA	BARCAP	FSWP	AIRESC	STI	CAS	BAI	INT	OCA	OTBM	DTBM	DSEAD	SSUP
SAFWAN - 2001															
SU25 1 22501	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	52/ 52	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	52/ 52	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
AR RUMAYLAH SW - 2002															
TOTAL	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
JALIBAH SE - 2003															
MIG23 22301	64/ 44	0/ 0	0/ 0	4/ 4	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL	64/ 44	0/ 0	0/ 0	4/ 4	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
SHAJBAH - 2004															
MIG21 22104	68/ 36	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL	68/ 36	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
AL MUFRASH - 2005															
SU25 2 22502	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	54/ 52	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	54/ 52	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
BASRAH WEST - 2006															
MIRAGE 20104	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	50/ 10	50/ 42	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	50/ 10	50/ 42	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TALLID - 2007															
MIRAGE 20103	0/ 0	0/ 0	0/ 0	6/ 6	0/ 0	46/ 32	0/ 0	0/ 0	0/ 0	16/ 16	6/ 6	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL	0/ 0	0/ 0	0/ 0	6/ 6	0/ 0	46/ 32	0/ 0	0/ 0	0/ 0	16/ 16	6/ 6	0/ 0	0/ 0	0/ 0	0/ 0
QALAT SALIH - 2008															
MIRAGE 20105	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	8/ 8	0/ 0	40/ 40	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	8/ 8	0/ 0	40/ 40	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
AMARA NEW - 2009															
TOTAL	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
NEJEFF NEW - 2010															
MIG29 22901	0/ 0	0/ 0	0/ 0	86/ 70	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL	0/ 0	0/ 0	0/ 0	86/ 70	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
UBAYDAH - 2011															
MIG23 22302	66/ 30	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL	66/ 30	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0

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TIME: 1:0000
 - 2:0000
 REPORT: AW-5

PART 1

 NUMBER OF SORTIES PLANNED / NUMBER OF SORTIES FLOWN

AIR BASE

NAME ID	DCA	ODCA	HVAA	BARCAP	FSWP	AIRESC	STI	CAS	BAI	INT	OCA	OTBM	DTBM	DSEAD	SSUP
SQUADRON															
SHAYKA MAZHAR - 2012	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
AL IKANDARIYAH - 2013															
MIG21 22101	70/22	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	70/22	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
BAGHDAD INTL - 2014															
MAINST 20000	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
BAGHDAD RASHEED - 2015															
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
BALAD SE - 2016															
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
AL MUHUMMADI - 2017															
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
AL ASAD - 2018															
MIG23 22303	76/2	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	76/2	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
MUDAYSIS - 2019															
MIG21 22105	72/4	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
MIRAGE 20102	60/10	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	32/16	0/0	0/0	0/0	0/0	0/0
TOTAL	132/14	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	32/16	0/0	0/0	0/0	0/0	0/0
H2 - 2020															
MIG21 22106	56/0	0/0	0/0	18/10	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	56/0	0/0	0/0	18/10	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
H3 - 2021															
MIG23 22304	76/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	76/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
H3 NW - 2022															
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0

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TIME: 1:0000
 2:0000
 REPORT: AW-5

PART 1

NUMBER OF SORTIES PLANNED / NUMBER OF SORTIES FLOWN

AIR BASE	NAME ID	SQUADRON	DCA	ODCA	HVAA	BARCAP	FSWP	AIRESC	STI	CAS	BAI	INT	OCA	OTBM	DTBM	DSEAD	SSUP
H3 SW - 2023			16/ 4	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	48/ 40	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
MIRAGE 20101			16/ 4	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	48/ 40	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL																	
H3 HWY - 2024			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL																	
AL TAQADDUM - 2025			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL																	
AL SAHRA - 2026			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL																	
TIKRIT EAST - 2027			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL																	
TIKRIT SOUTH - 2028			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL																	
K2 - 2029			72/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
MIG21 22102			72/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL																	
AL FATHAH - 2030			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL																	
QAYYARAH - 2031			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL																	
KIRKUK - 2032			72/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
MIG21 22103			72/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL																	
IRBIL - 2033			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL																	
MOSEL - 2034			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL																	
TALL AFAR - 2035			0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
TOTAL																	

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TIME: 1:0000
 - 2:0000
 REPORT: AW-5

PART 1

 NUMBER OF SORTIES PLANNED / NUMBER OF SORTIES FLOWN

AIR BASE	NAME	ID	DCA	ODCA	HVAA	BARCAP	FSWP	AIRESC	STI	CAS	BAI	INT	OCA	OTBM	DTBM	DSEAD	SSUP
KUWAIT INTL - 2036			0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL			0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
AHMED AL JABER - 2037			0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL			0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
ALI AL SALEM - 2038			0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL			0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
2ND SCUD - 29902			0/0	0/0	0/0	0/0	0/0	0/0	6/6	0/0	0/0	10/10	0/0	0/0	0/0	0/0	0/0
TOTAL			0/0	0/0	0/0	0/0	0/0	0/0	6/6	0/0	0/0	10/10	0/0	0/0	0/0	0/0	0/0
3RD SCUD - 29903			0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	16/15	0/0	0/0	0/0	0/0	0/0
TOTAL			0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	16/15	0/0	0/0	0/0	0/0	0/0
4TH SCUD - 29904			0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	16/16	0/0	0/0	0/0	0/0
TOTAL			0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	16/16	0/0	0/0	0/0	0/0
1ST SCUD - 29901			0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	12/12	0/0	0/0	0/0	0/0
TOTAL			0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	12/12	0/0	0/0	0/0	0/0

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TIME: 1:0000
 - 2:0000
 REPORT: AW-5
 PART 2

NUMBER OF SORTIES PLANNED / NUMBER OF SORTIES FLOWN

AIR BASE	NAME ID	SQUADRON	CSUP	ESCSUP	SJAM	CJAM	ESCJAM	RECE	SREC	AEW	AAR	LIFT	XXXX	RESERVE	DISPERS	TOTAL
SAFWAN - 2001																
	SU25 1	22501	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	52/52
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	52/52
AR RUMAYLAH SW - 2002																
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
JALIBAH SE - 2003																
	MIG23	22301	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	68/48
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	68/48
SHAIBAH - 2004																
	MIG21	22104	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	68/36
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	68/36
AL MUFRAH - 2005																
	SU25 2	22502	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	54/52
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	54/52
BASRAH WEST - 2006																
	MIRAGE	20104	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	100/52
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	100/52
TALLID - 2007																
	MIRAGE	20103	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	82/68
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	82/68
QALAT SALIH - 2008																
	MIRAGE	20105	0/0	38/26	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	86/74
	TOTAL		0/0	38/26	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	86/74
AMARA NEW - 2009																
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
NEJEF NEW - 2010																
	MIG29	22901	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	86/70
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	86/70
UBAYDAH - 2011																
	MIG23	22302	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	66/30
	TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	66/30

 * S O R T I E G E N E R A T I O N
 * A I R B A S E A N D S Q U A D R O N
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TIME: 1:0000
 - 2:0000
 REPORT: AW-5

PART 2

NUMBER OF SORTIES PLANNED / NUMBER OF SORTIES FLOWN

AIR BASE

NAME ID	CSUP	ESCSUP	SJAM	CJAM	ESCJAM	RECCE	SREC	AEW	AAR	LIFT	XXXX	RESERVE	DISPERS	TOTAL
SHAYKA MAZHAR - 2012														
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
AL IKANDARIYAH - 2013														
MIG21 22101	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
BAGHDAD INTL - 2014														
MAINST 20000	0/0	0/0	0/0	0/0	0/0	0/0	0/0	3/3	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	3/3	0/0	0/0	0/0	0/0	0/0	0/0
BAGHDAD RASHEED - 2015														
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
BALAD SE - 2016														
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
AL MUHUMMADI - 2017														
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
AL ASAD - 2018														
MIG23 22303	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
MUDAYSIS - 2019														
MIG21 22105	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
MIRAGE 20102	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
H2 - 2020														
MIG21 22106	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
H3 - 2021														
MIG23 22304	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
H3 NW - 2022														
TOTAL	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0

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TIME: 1:0000
 - 2:0000
 REPORT: AW-5
 PART 2

NUMBER OF SORTIES PLANNED / NUMBER OF SORTIES FLOWN

AIR BASE NAME ID SQUADRON	CSUP	ESCSUP	SJAM	CJAM	ESCJAM	RECCE	SREC	AEW	AAR	LIFT	XXXX	RESERVE	DISPERS	TOTAL
H3 SW - 2023														
MIRAGE 20101	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/
TOTAL	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	64/ 44
H3 HWY - 2024														
TOTAL	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/
AL TAQADDUM - 2025														
TOTAL	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/
AL SAHRA - 2026														
TOTAL	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/
TIKRIT EAST - 2027														
TOTAL	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/
TIKRIT SOUTH - 2028														
TOTAL	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/
K2 - 2029														
MIG21 22102	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/
TOTAL	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	72/ 0
AL FATHAH - 2030														
TOTAL	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/
QAYYARAH - 2031														
TOTAL	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/
KIRKUK - 2032														
MIG21 22103	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/
TOTAL	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	72/ 0
IRBIL - 2033														
TOTAL	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/
MOSEL - 2034														
TOTAL	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/
TALL AFAR - 2035														
TOTAL	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/	0/

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TIME: 1:0000
 - 2:0000
 REPORT: AW-5

PART 2

 NUMBER OF SORTIES PLANNED / NUMBER OF SORTIES FLOWN

AIR BASE	NAME ID	CSUP	ESCSUP	SJAM	CJAM	ESCJAM	RECCE	SSEC	AEW	AAR	LIFT	XXXX	RESERVE	DISPERS	TOTAL
KUWAIT INTL - 2036		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
AHMED AL JABER - 2037		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
ALI AL SALEM - 2038		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
2ND SCUD - 29902		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
2ND SC 29902		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
3RD SCUD - 29903		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
3RD SC 29903		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
4TH SCUD - 29904		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
4TH SC 29904		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
1ST SCUD - 29901		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
1ST SC 29901		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
TOTAL		0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0

Appendix B: Table of Distribution Expected Values

Distribution	Probability Function	Expected Value
Beta	$f(y) = \left[\frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} \right] y^{\alpha-1}(1-y)^{\beta-1}$ $0 < y < 1$	$\frac{\alpha}{\alpha + \beta}$
Binomial	$p(y) = \binom{n}{y} p^y (1-p)^{n-y}$ $y = 0, 1, \dots, n$	np
Erlang	$f(y) = \frac{1}{\lambda} e^{-\frac{y}{\lambda}} \frac{\left(\frac{y}{\lambda}\right)^{n-1}}{(n-1)!}$ $0 < y$	$k\beta$
Exponential	$f(y) = \frac{1}{\beta} e^{-y/\beta}$ $0 < \beta; 0 < y < \infty$	β
Gamma	$f(y) = \left[\frac{1}{\Gamma(\alpha)\beta^\alpha} \right] y^{\alpha-1} e^{-\frac{y}{\beta}}$ $0 < y < \infty$	$\alpha\beta$
Logarithmic Normal	$f(y) = \frac{1}{y\sigma\sqrt{2\pi}} e^{\left[-\left(\frac{1}{2\sigma^2}\right)(\ln y - \mu)^2\right]}$ $0 < y$	$e^{\frac{\mu + \sigma^2}{2}}$
Normal	$f(y) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left[-\left(\frac{1}{2\sigma^2}\right)(y - \mu)^2\right]}$ $-\infty < y < +\infty$	μ
Poisson	$p(y) = \frac{\lambda^y e^{-\lambda}}{y!}$ $y = 0, 1, 2, \dots$	λ
Randi Discrete Uniform (a, b)	$p(y) = \frac{1}{(b-a+1)}$ $y = a, a+1, \dots, b-1, b$	$\frac{\sum_{i=a}^b i}{(b-a+1)}$

Distribution	Probability Function	Expected Value
Random Uniform (0, 1)	$f(y) = \frac{1}{1}$ $0 \leq y \leq 1$	0.5
Triangle	$f(y) = \begin{cases} \frac{2(y-a)}{(b-a)(c-a)} & a \leq y \leq c \\ \frac{2(b-y)}{(b-a)(b-c)} & c < y \leq b \end{cases}$ $a \leq y \leq b$	$\frac{a+b+c}{3}$
Uniform	$f(y) = \frac{1}{\theta_2 - \theta_1}$ $\theta_1 \leq y \leq \theta_2$	$\frac{\theta_1 + \theta_2}{2}$
Weibull	$f(y) = \alpha \beta^{-\alpha} y^{\alpha-1} e^{-\left(\frac{y}{\beta}\right)^\alpha}$ $0 \leq y$	$\beta \Gamma\left(1 + \frac{1}{\alpha}\right)$

Appendix C: The Modified and Added Files

The modified SIMSCRIPT II.5 files located in the *Source* directory:

ADF040.sim	AIR042.sim	AIR830.sim	GRD300.sim	REC012.sim
ADF041.sim	AIR050.sim	AIR840.sim	GRD302.sim	REC013.sim
ADF101.sim	AIR051.sim	AIR911.sim	GRD309.sim	REC014.sim
ADF105.sim	AIR060.sim	AIR920.sim	GRD871.sim	REC015.sim
ADF121.sim	AIR070.sim	ANT211.sim	ISR000.sim	REC016.sim
ADF140.sim	AIR101.sim	BSE001.sim	ISR001.sim	REC017.sim
ADF150.sim	AIR110.sim	BSE002.sim	ISR004.sim	REC018.sim
ADF160.sim	AIR120.sim	BSE003.sim	ISR005.sim	REC310.sim
ADF161.sim	AIR150.sim	BSE020.sim	ISR115.sim	REC320.sim
ADF200.sim	AIR241.sim	BSE050.sim	ISR250.sim	REC330.sim
ADF420.sim	AIR526.sim	BSE200.sim	ISR251.sim	REC341.sim
ADF430.sim	AIR528.sim	BSE201.sim	ISR360.sim	REC900.sim
ADF440.sim	AIR540.sim	BSE225.sim	ISR365.sim	UTL104.sim
ADF452.sim	AIR550.sim	BSE251.sim	ISR400.sim	UTL260.sim
ADF460.sim	AIR561.sim	BSE260.sim	ISR500.sim	UTL305.sim
ADF500.sim	AIR564.sim	BSE270.sim	LOG700.sim	UTL520.sim
AIR014.sim	AIR567.sim	BSE400.sim	PLA010.sim	UTL550.sim
AIR017.sim	AIR602.sim	BSE800.sim	PLA443.sim	UTL750.sim
AIR021.sim	AIR800.sim	GRD095.sim	PLA557.sim	UTL920.sim
AIR041.sim	AIR810.sim	GRD100.sim	REC011.sim	STA900.sim

The added SIMSCRIPT II.5 files located in the *Source* directory:

ZEARL1.sim
ZEARL2.sim

The modified THUNDER scripts located in the *bin* directory:

ttrun
ttrep
ttcompile
ttuser.each

The modified ME data files located in the *Data/ME* directory:

control.dat

The added ME data files located in the *Data/ME* directory:

newseed.val

The added C files located in the *Source* directory:

RngStream.c

RngStream.h

Appendix D: CONTROL.DAT File

CONTROLS.020

```
REPORT.TITLE                "ME"

BASIC.SIMULATION.CONTROLS
  NUMBER.OF.DAYS.OF.WAR(INT.DAYS)      5
  BEGIN.DAYLIGHT(DEC.HOURS)            6.00
  END.DAYLIGHT(DEC.HOURS)              18.00
  ADX.PROVIDE.TERM.AD.FOR.FIXED.TGTS   YES
  IGNORE.RANGE.CONSTRAINTS            NO
  COUNT.ALERT.MSN.AS.COMPLETE         NO
END.BASIC.SIMULATION.CONTROLS

GAME.CONTROLS
  GAME.FILE.MOD.FLAG                 YES
  GAME.ENABLE                         NO
  GAME.CYCLE                          24
  FIRST.GAME.STOP(DAYS)              2.0
END.GAME.CONTROLS

ADF.CALIBRATION.CONTROLS
  ADF.CALIBRATION.MODE.ENABLE         NO
@   if enabled
@   only preplanned ATOs fly
@   all ADvsAC Pks = 0.0
@   unlimited AD ammo reloads
@   lethal SEAD disabled
@   air-to-ground disabled
@   special ADF calibration transactions enabled
@   ADF results averaged over multiple reps:
  REPLICATIONS.PER.ADF.CALCULATION     500
  USE.MANUAL.IADS.VALUES(YES,NO)       NO
  MANUAL.IADS.INTEGRATION.LEVEL(0.0-1.0) 0.7
  MANUAL.IADS.SECONDS.DELAY             15.0
  MANUAL.IADS.INTIMIDATE                0.0
END.ADF.CALIBRATION.CONTROLS

COMPUTATIONAL.RESOLUTION.LEVELS(LOW,HIGH,VERY.HIGH)
  BLUE.AIR.DEFENSE                     HIGH
  RED.AIR.DEFENSE                       HIGH
  AIR.WAR                               HIGH
  BLUE.RECONNAISSANCE                   HIGH
  RED.RECONNAISSANCE                     HIGH
  WEATHER                               HIGH
  GROUND.MOVEMENT                       HIGH
  CRITICAL.RESOURCE                      HIGH
END.COMPUTATIONAL.RESOLUTION.LEVELS

GRAPHIC.OUTPUT.CONTROLS
  WRITE.GRAPHIC.TO.TRANS                NO
```


POST . PROCESS . GRAPHICS (BOTH , CHART , MAP , NONE)	BOTH
AD . COMPLEX . STATUS . UPDATE . CYCLE (HOURS)	6
AIRBASE . STATUS . UPDATE . CYCLE (HOURS)	3
CHOKE . POINT . STATUS . UPDATE . CYCLE (HOURS)	6
COMMAND . STATUS . UPDATE . CYCLE (HOURS)	6
LOG . FAC . STATUS . UPDATE . CYCLE (HOURS)	6
STRATEGIC . TARGET . STATUS . UPDATE . CYCLE (HOURS)	6
SUPPLY . TRAIN . STATUS . UPDATE . CYCLE (HOURS)	6
TBM . UNIT . STATUS . UPDATE . CYCLE (HOURS)	6
UNIT . STATUS . UPDATE . CYCLE (HOURS)	6
PERCEPT . STATUS . UPDATE . CYCLE (HOURS)	6
AIR . REPORT . CYCLE (DAY , GAME , BLUE , RED)	DAY

END . OUTPUT . CONTROLS

OVERALL . REPORT . CONTROLS

REPORT . MODE (STANDARD , METRIC , BOTH)	STANDARD
--	----------

END . OVERALL . REPORT . CONTROLS

DATA . REPORT . CONTROLS

NUMBER . OF . DATA . REPORTS		91
CONTROL . FILE	DR-2	NO
RANDOM . SEEDS	DR-3	NO
STANDARD . TARGETS	DR-5	NO
STANDARD . TARGET . REPAIR . PROBS	DR-6	NO
TYPE . RADAR	DR-10	NO
TYPE . JAMMER	DR-11	NO
AIR . DEFENSE . DATA . REPORTS	****	
TYPE . AIR . DEFENSE	DR-12	NO
POSTURES . & . CLASSES	DR-13	NO
THREAT . CLASSES	DR-16	NO
INTEGRATED . AD . SYSTEM	DR-14	NO
ADA . ENGAGEMENT . PROBS	DR-15	NO
AD . VS . AIRCRAFT . PKS	DR-27	NO
AD . COMPLEXES	DR-66	NO
PLANNING . DATA . REPORTS	****	
AIR . RULES	DR-20	NO
AIR . PLANNING . RULES	DR-79	NO
AIR . ALLOCATION	DR-21	NO
AIR . PLANNING . FACTORS	DR-67	NO
OCA . TARGETS	DR-23	NO
PREPLANNED . ATOS	DR-29	NO
PREPLANNED . LIFT . ATOS	DR-22	NO
ZONE . SECTOR . TGT . PRIORITY	DR-65	NO
INT . DEPTH . FACTOR . CURVES	DR-68	NO
STI . TARGETS	DR-70	NO
AIR . TO . AIR . DATA . REPORTS	****	
AIR . TO . AIR . PKS	DR-24	NO
RELEASE . RANGE . ADVANTAGE	DR-25	NO
CONFIG . DETECT . PROBS	DR-26	NO
AIR . TO . GROUND . PKS	DR-28	NO
HARM . PKS	DR-40	NO
MINE . PKS	DR-41	NO
TAKEOFF . LANDING . PKS	DR-42	NO
WMD . EFFECTS	DR-43	NO
TYPE . AIR . MUNITIONS	DR-31	NO

MUNITION.SURVIVABILITY.CURVES	DR-44	NO
TYPE.AIRCRAFT	DR-32	NO
AIRCRAFT.MAINTENANCE	DR-39	NO
TBM.UNITS	DR-75	NO
TBM.DETECTION	DR-76	NO
AIRBASE	DR-33	NO
CARRIER.BATTLE.GROUP	DR-30	NO
SUPPLY.KIT	DR-34	NO
SQUADRON	DR-35	NO
AIR.TO.GRD.MIN.CEIL.VIS	DR-36	NO
SUPPLY.URGENCY.CURVES	DR-37	NO
CRITICAL.RESOURCE	DR-38	NO
NODES	DR-45	NO
TRANS.SHIPMENT.POINTS	DR-46	NO
ARCS	DR-47	NO
CHOKE.POINTS	DR-48	NO
MINE.DELAY.CURVES	DR-49	NO
BATTLEFIELD	DR-50	NO
AIR.NETWORK	DR-73	NO
GROUND.TARGET.ACQUISITION	DR-51	NO
TARGET.ACQUISITION.CURVES	DR-17	NO
TERRAIN	DR-52	NO
INTERVISIBILITY.CURVES	DR-53	NO
TYPE.C3.FACILITY	DR-55	NO
COMMAND	DR-56	NO
GROUND.RULES	DR-57	NO
SUPPLY.TRAIN.TARGETS	DR-54	NO
LOGISTIC.FACILITY	DR-58	NO
TYPE.UNIT	DR-59	NO
TYPE.EQUIPMENT	DR-60	NO
EQUIPMENT.SIZE.CATEGORY	DR-61	NO
WEAPON.VS.EQUIPMENT.EFFECTS	DR-62	NO
UNIT	DR-63	NO
LIFT.EVENTS	DR-82	NO
LOG.RULES	DR-81	NO
SPACE.LOGISTICS	DR-78	NO
PERCEPTIONS	DR-64	NO
STRATEGIC.TARGETS	DR-69	NO
AIRCRAFT.FACTORS	DR-71	NO
GROUND.WAR.SUPPORT.EFFECTS	DR-72	NO
BOOST.PHASE.INTERCEPT	DR-77	NO
TARGET.AVAILABILITY	DR-74	NO
WEATHER.STATIONS	DR-80	NO
SATELLITE.NAV.JAM.STATES	DR-92	NO
SATELLITE.NAV.MUNT.EFFECTS	DR-93	NO
SATELLITE.PASSES	DR-94	NO
ISR.DATA.REPORTS	****	
ISR.SATELLITES	DR-83	NO
ISR.PLANNING	DR-84	NO
ISR.TARGETS	DR-85	NO
ISR.SENSORS.AND.EMITTERS	DR-86	NO
ISR.EFFECTS	DR-87	NO
ISR.INITIALIZATION	DR-88	NO
ISR.EVENTS	DR-89	NO
ISR.NODES	DR-90	NO

ISR.SENSOR.VS.EMITTER.PROBS	DR-91				NO
MUNITION.MANAGEMENT.FACTORS	DR-95				NO
CHEMICAL.WEAPON.EFFECTS	DR-96				NO
CHEMICAL.AGENT.DELIVERY	DR-97				NO
CAMPAIGN.COST.DATA	DR-99				NO
END.DATA.REPORT.CONTROLS					
OUTPUT.REPORT.CONTROLS					
COMPLETED.MISSION.INFO	AW-1	NO	BOTH	0.00	300.00
DAILY.AIR.WAR.RESULTS.SUMMARIES					

MISSION.&.SORTIE.SUMMARY	AW-2	NO	BOTH	0.00	300.00
AIRCRAFT.LOSS.SUMMARY	AW-3	YES	BOTH	0.00	300.00
AIRBASE.ACTIVITY	AW-4	NO	BOTH	0.00	300.00
SORTIE.GENERATION	AW-5	YES	BOTH	0.00	300.00
CANCELLED.MISSION.INFO	AW-6	NO	BOTH	0.00	300.00
INDIVIDUAL.MISSION.KILL.RESULTS					

DCA.MISSION.KILLS	AW-7	NO	BOTH	0.00	300.00
ODCA.MISSION.KILLS	AW-8	NO	BOTH	0.00	300.00
HVAA.MISSION.KILLS	AW-9	NO	BOTH	0.00	300.00
BARCAP.MISSION.KILLS	AW-10	NO	BOTH	0.00	300.00
FSWP.MISSION.KILLS	AW-11	NO	BOTH	0.00	300.00
DTBM.MISSION.KILLS	AW-12	NO	BOTH	0.00	300.00
STI.MISSION.KILLS	AW-13	NO	BOTH	0.00	300.00
CAS.MISSION.KILLS	AW-14	NO	BOTH	0.00	300.00
BAI.MISSION.KILLS	AW-15	NO	BOTH	0.00	300.00
INT.MISSION.KILLS	AW-16	NO	BOTH	0.00	300.00
OCA.MISSION.KILLS	AW-17	NO	BOTH	0.00	300.00
DSEAD.MISSION.KILLS	AW-18	NO	BOTH	0.00	300.00
SUPPRESSION.MISSION.KILLS	AW-19	NO	BOTH	0.00	300.00
OTBM.MISSION.KILLS	AW-20	NO	BOTH	0.00	300.00
AIR.ESCORT.MISSION.KILLS	AW-21	NO	BOTH	0.00	300.00
HIGH.VALUE.ASSET.ACTIVITY	AW-22	NO	BOTH	0.00	300.00
DEFENDING.AIRCRAFT.KILLS	AW-23	NO	BOTH	0.00	300.00
LIFT.MISSION	AW-24	NO	BOTH	0.00	300.00
AIRCRAFT.MAINTENANCE					

TYPE.AIRCRAFT.MX.ACTIVITY	MX-1	NO	BOTH	0.00	300.00
CONSUM.RESOURCE.ACTIVITY	MX-2	NO	BOTH	0.00	300.00
NON.CONSUM.RES.ACTIVITY	MX-3	NO	BOTH	0.00	300.00
GROUND.COMBAT.CYCLE.REPORTS					

UNIT.STATUS	CC-1	NO	BOTH	0.00	300.00
C3.FACILITY.STATUS	CC-2	NO	BOTH	0.00	300.00
CHOKE.POINT.STATUS	CC-3	NO	BOTH	0.00	300.00
FLOT.MOVEMENT	CC-4	NO	BOTH	0.00	300.00
AIR.GRID.AD.STATUS	CC-5	NO	BOTH	0.00	300.00
TYPE.AD.SITE.STATUS	CC-6	NO	BOTH	0.00	300.00
STRATEGIC.TARGET.STATUS	CC-7	NO	BOTH	0.00	300.00
IADS.OBJECT.STATUS	CC-8	NO	BOTH	0.00	300.00
AIR.MISSION.PLANNING.REPORTS					

APPORTIONMENT.ALLOCATION	MP-1	NO	BOTH	0.00	300.00
AIR.TASKING.ORDERS	MP-2	NO	BOTH	0.00	300.00
SORTIES.SCHEDULED.SUMMARY	MP-3	NO	BOTH	0.00	300.00
TARGET.PRIORITIES	MP-4	NO	BOTH	0.00	300.00
AIR.REFUELING.ALLOCATION	MP-5	NO	BOTH	0.00	300.00
AIR.PLANNING.RULE.STATUS	MP-6	NO	BOTH	0.00	300.00
GROUND.SUPPLY.CYCLE.REPORTS					

LOGISTIC.FACILITY.STATUS	SC-1	NO	BOTH	0.00	300.00
SUPPLY.TRAIN.STATUS	SC-2	NO	BOTH	0.00	300.00
CRITICAL.RESOURCE.STATUS	SC-3	NO	BOTH	0.00	300.00
SPACE.LOGISTICS.REPORT	SL-1	NO	BOTH	0.00	300.00

END.OUTPUT.REPORT.CONTROLS

GAME.REPORT.SELECTION

GC-1	NO	BOTH	"AIR COMMAND MISSION ALLOCATION REPORT"
GC-2	NO	BOTH	"AIR COMMAND RESOURCE ALLOCATION REPORT"
GC-3	NO	BOTH	"TARGET PRIORITY REPORT"
GC-4	NO	BOTH	"GROUND COMMAND STRUCTURE WITH SUPPORTING AIR COMMANDS"
GC-5	NO	BOTH	"AIR COMMAND STRUCTURE WITH SUPPORTED GROUND COMMANDS"
GC-6	NO	BOTH	"AIR BASE ASSETS REPORT"
GC-7	NO	BOTH	"LOGISTICS FACILITY ASSETS REPORT"
GC-8	NO	BOTH	"AIRCRAFT CHARACTERISTICS REPORT"
GC-9	NO	BOTH	"ZONE SECTOR PERCEPTION HISTORY"
GC-10	NO	BOTH	"FLOT MOVEMENT REPORT"
GC-11	NO	BOTH	"MISSION ALLOCATION PROJECTION"
GC-12	NO	BOTH	"PROJECTED AIR TASKING ORDERS"
GC-13	NO	BOTH	"PROJECTED SORTIES SCHEDULED"
GC-14	NO	BOTH	"AIRCRAFT PLANNING FACTORS"
GC-15	NO	BOTH	"PREPLANNED ATO REPORT"
GC-16	NO	BOTH	"AIR GRID AIR DEFENSE SITE STATUS"
GC-17	NO	BOTH	"AIR COMBAT RULES"
GC-18	NO	BOTH	"AIR PLANNING RULES"
GC-19	NO	BOTH	"PREPLANNED LIFT ATO REPORT"
GC-20	NO	BOTH	"MUNITION MANAGEMENT FACTORS"

END.GAME.REPORT.SELECTION

TRANSACTION.CONTROLS

@DEBUG.TRANSACTIONS

ADFL	0	0.000	300.00
ADFH	0	0.000	300.00
AIRA	0	0.000	300.00
AIRF	0	0.000	300.00
AIRG	0	0.000	300.00
AIRP	0	0.000	300.00
ANTC	0	0.000	300.00
ANTI	0	0.000	300.00
ANTP	0	0.000	300.00
BSEL	0	0.000	300.00
BSEM	0	0.000	300.00
BSEO	0	0.000	300.00
CONA	0	0.000	300.00
GRDC	0	0.000	300.00
GRDM	0	0.000	300.00
GRDO	0	0.000	300.00
ISRE	0	0.000	300.00
ISRP	0	0.000	300.00
ISRR	0	0.000	300.00
ISRS	0	0.000	300.00
ISRT	0	0.000	300.00
LOGS	0	0.000	300.00
LOGE	0	0.000	300.00

NETM	0	0.000	300.00	
NETP	0	0.000	300.00	
PLAA	0	0.000	300.00	
PLAT	0	0.000	300.00	
RECT	0	0.000	300.00	
RULP	0	0.000	300.00	
SATL	0	0.000	300.00	
SATO	0	0.000	300.00	
STAA	0	0.000	300.00	
UTLA	0	0.000	300.00	
UTLG	0	0.000	300.00	
UTLF	0	0.000	300.00	
WTHH	0	0.000	300.00	
@GRAPHIC.TRANSACTIONS				
GRAA	3	0.000	300.00	
GRAG	4	0.000	300.00	
GRAI	2	0.000	300.00	
@ANALYSIS.TRANSACTIONS				
EQ.KILLS	0	0.000	300.000	
AA.KILLS	0	0.000	300.000	
SA.KILLS	0	0.000	300.000	
MUNT.EXP	0	0.000	300.000	
STR.TGT	0	0.000	300.000	
AA.ENC	0	0.000	300.000	
@DATABASE.TRANSACTIONS				
DB.PLAN	0	0.000	300.000	
DB.EXEC	0	0.000	300.000	
DB.STATE	0	0.000	300.000	
@RMS.TRANSACTIONS				
RMSPP	0	0.000	300.000	
@MP.TRANSACTIONS				
MPPP	0	0.000	300.000	
@AIR.LIFT.TRANSACTIONS				
ALFT	0	0.000	300.000	
@ISR.TRANSACTIONS				
BPIPP	0	0.000	300.000	
ISRPP	0	0.000	300.000	
ISRPP2	0	0.000	300.000	
@SURVIVE.TRANSACTIONS				
SURVIVE	0	0.000	300.000	
@WARGAME.TRANSACTIONS				
WARGAME	0	0.000	300.000	
@GRAPHER.2000.TRANSACTIONS				
GRAPHER2K	0	0.000	300.000	
END.TRANSACTION.CONTROLS				
VARIANCE.REDUCTION.CONTROLS				
USE.NEW.RANDOM.NUMBER.GENERATOR				YES
USE.COMMON.RANDOM.NUMBERS				YES
USE.ANTITHETIC.VARIABLES				NO
USE.CONTROL.VARIATES				YES
RANDOM.NUMBER.STREAM.DATA				
READ.RANDOM.SEEDS				YES

WRITE .RANDOM. SEEDS	YES
SINGLE .SEED. ALL .NUMBERS	NO
SINGLE .SEED. IS (INT)	1

RN .STREAMS

ADF040.1	1
ADF041.1	1
ADF041.2	1
ADF041.3	1
ADF101.1	1
ADF101.2	1
ADF105.1	1
ADF121.1	1
ADF121.2	1
ADF121.3	1
ADF140.1	1
ADF140.2	1
ADF140.3	1
ADF150.1	1
ADF150.2	1
ADF150.3	1
ADF150.4	1
ADF150.5	1
ADF150.6	1
ADF150.7	1
ADF160.1	1
ADF161.1	1
ADF161.2	1
ADF161.3	1
ADF161.4	1
ADF161.5	1
ADF200.1	1
ADF420.1	1
ADF420.2	1
ADF420.3	1
ADF430.1	1
ADF430.2	1
ADF430.3	1
ADF440.1	1
ADF440.2	1
ADF440.3	1
ADF452.1	1
ADF452.2	1
ADF452.3	1
ADF452.4	1
ADF452.5	1
ADF452.6	1
ADF452.7	1
ADF460.1	1
ADF460.2	1
ADF500.1	1
AIR007.1	1
AIR017.1	1
AIR041.1	1
AIR041.2	1

AIR041.3	1
AIR042.1	1
AIR042.2	1
AIR050.1	1
AIR050.2	1
AIR051.1	1
AIR060.1	1
AIR060.2	1
AIR060.3	1
AIR070.1	1
AIR070.2	1
AIR021.1	1
AIR101.1	1
AIR101.2	1
AIR110.1	1
AIR120.1	1
AIR150.1	1
AIR150.2	1
AIR241.1	1
AIR526.1	1
AIR528.1	1
AIR540.1	1
AIR550.1	1
AIR550.2	1
AIR561.1	1
AIR561.2	1
AIR564.1	1
AIR567.1	1
AIR567.2	1
AIR602.1	1
AIR800.1	1
AIR800.2	1
AIR800.3	1
AIR810.1	1
AIR810.2	1
AIR830.1	1
AIR830.2	1
AIR830.3	1
AIR830.4	1
AIR840.1	1
AIR840.2	1
AIR840.3	1
AIR840.4	1
AIR911.1	1
AIR911.2	1
AIR920.1	1
ANT211.1	1
ANT211.2	1
ANT211.3	1
BSE001.1	1
BSE001.2	1
BSE002.1	1
BSE002.2	1
BSE003.1	1
BSE003.2	1

BSE020.1	1
BSE030.1	1
BSE050.1	1
BSE050.2	1
BSE200.1	1
BSE200.2	1
BSE200.3	1
BSE200.4	1
BSE200.5	1
BSE201.1	1
BSE201.2	1
BSE251.1	1
BSE260.1	1
BSE260.2	1
BSE270.1	1
BSE400.1	1
BSE800.1	1
GRD095.1	1
GRD095.2	1
GRD095.3	1
GRD100.1	1
GRD300.1	1
GRD302.1	1
GRD309.1	1
GRD871.1	1
GRD871.2	1
ISR000.1	1
ISR000.2	1
ISR000.3	1
ISR000.4	1
ISR001.1	1
ISR001.2	1
ISR001.3	1
ISR004.1	1
ISR005.1	1
ISR115.1	1
ISR115.2	1
ISR250.1	1
ISR250.2	1
ISR251.1	1
ISR251.2	1
ISR251.3	1
ISR251.4	1
ISR360.1	1
ISR365.1	1
ISR400.1	1
ISR500.1	1
ISR500.2	1
ISR500.3	1
LOG700.1	1
LOG700.2	1
LOG700.3	1
PLA010.1	1
PLA010.2	1
PLA443.1	1

PLA557.1	1
REC011.1	1
REC011.2	1
REC011.3	1
REC012.1	1
REC012.2	1
REC012.3	1
REC012.4	1
REC012.5	1
REC012.6	1
REC013.1	1
REC013.2	1
REC013.3	1
REC013.4	1
REC013.5	1
REC013.6	1
REC014.1	1
REC014.2	1
REC014.3	1
REC014.4	1
REC014.5	1
REC014.6	1
REC014.7	1
REC014.8	1
REC014.9	1
REC015.1	1
REC015.2	1
REC015.3	1
REC015.4	1
REC015.5	1
REC015.6	1
REC015.7	1
REC015.8	1
REC016.1	1
REC016.2	1
REC016.3	1
REC016.4	1
REC016.5	1
REC016.6	1
REC016.7	1
REC016.8	1
REC016.9	1
REC016.10	1
REC016.11	1
REC017.1	1
REC017.2	1
REC017.3	1
REC017.4	1
REC017.5	1
REC017.6	1
REC017.7	1
REC017.8	1
REC017.9	1
REC017.10	1
REC018.1	1

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REC018.2 1
REC018.3 1
REC018.4 1
REC310.1 1
REC310.2 1
REC320.1 1
REC320.2 1
REC320.3 1
REC330.1 1
REC330.2 1
REC330.3 1
REC330.4 1
REC330.5 1
REC330.6 1
REC330.7 1
REC330.8 1
REC341.1 1
REC341.2 1
REC341.3 1
REC341.4 1
REC900.1 1
REC900.2 1
UTL104.1 1
UTL305.1 1
UTL520.1 1
UTL520.2 1
UTL550.1 1
UTL550.2 1
UTL750.1 1
UTL920.1 1
ISR000.5 1
ADF140.4 1
ADF440.4 1
AIR830.5 1
AIR830.6 1
ISR251.5 1
ISR251.6 1
ISR251.7 1
LOG700.4 1
END . RN . STREAMS
END . RANDOM . NUMBER . STREAM . DATA

END . CONTROL
```

Appendix E: Example SIMSCRIPT II.5 Code AIR070.SIM (Original)

```
ROUTINE AIR.070.ADJUDICATE.DTBM
  '$Id: air070.sim,v 2.10 2000/09/20 20:12:38 steveh Exp $

GIVEN
  .DTBM.PLATFORM,      ''PTR TO DTBM PLATFORM FIRING AT TBM
  .DTBM.WPN.TYPE,      ''TYPE OF SHOOTER ENGAGING TBM
  .TBU,                ''INDEX OF TBM.UNIT LAUNCHING TBM
  .TBM.FLT,            ''POINTER TO TBM FLIGHT BEING LAUNCHED
  .DETECT.SECONDS.DELAY ''BETWEEN TBM LAUNCH AND DTBM RESPONSE

''YIELDING
''  NONE

''PURPOSE
''-----
''  ADJUDICATE A DTBM VS. TBM AIR-TO-AIR ENGAGEMENT

''PROCESSING
''-----
''

''=====
''CALLED BY
''-----
''  AIR.060.BOOST.PHASE.INTERCEPT.MANAGER

''CHANGE LOG
''-----
''  DATE          AUTHOR          CHANGE SUMMARY
''-----
''  1-11-96       MORGAN          INITIAL IMPLEMENTATION
''  1-23-96       EMERT           REPLACED .TBT WITH .TTT
''  2-6-96        MORGAN          SET FL.ENGAGE.FLAG
''  2-9-96        MORGAN          DISPLAY ENGAGEMENTS ALONG TBM PATH
''  6-12-96       MORGAN          MAKE LASER SHOT TIME A DISTRIBUTION
''  8-09-99       HADLEY          FLIGHT GROUP MISSION STATS MAY HAVE
''                BEEN CREATED EARLIER
''  08-16-99      LENNOX          CALL GRA.730, GRA.740 FOR GRAPHER2K
''  2-11-00       COSGROVE        ADD SBL
''  07-10-00      HADLEY          UP FLIGHT GROUP ID IN TRANS TO I 7
''=====

NORMALLY MODE IS INTEGER
DEFINE .DETECT.SECONDS.DELAY, .PK, .SHOT.DURATION.SEC, .SUM.SECONDS,
      .TOTAL.ELAPSED.SECONDS
      AS DOUBLE VARIABLES

IF .DTBM.WPN.TYPE = ..SPACE.BASED.LASER
  LET .DTBM.SAT = .DTBM.PLATFORM
ELSE
```

```

LET .DTBM.FG = .DTBM.PLATFORM

LET .DTBM.FLT = F.FG.FLIGHT.SET(.DTBM.FG)
IF FL.MISSION(.DTBM.FLT) <> ..DTBM
    TRACE
    STOP
    OTHERWISE
ALWAYS

LET .TBM.FG = FL.FLT.GP(.TBM.FLT)
LET .TBM.LAUNCH.X = TBU.X.COORD(.TBU)
LET .TBM.LAUNCH.Y = TBU.Y.COORD(.TBU)
LET .TBM.TAC = TBU.TYPE.AC(.TBU)
LET .TTT = TA.TBM.TARGET.TYPE(.TBM.TAC)
LET .TBM.TGT = FG.TARGET(.TBM.FG)
LET .TBM.TGT.X = TG.X.COORD(.TBM.TGT)
LET .TBM.TGT.Y = TG.Y.COORD(.TBM.TGT)

IF .DTBM.WPN.TYPE = ..SPACE.BASED.LASER
    LET .TSW = SAT.TYPE.SPACE.WPN(.DTBM.SAT)
    LET .DWP = TSW.DTBM.WEAPON(.TSW)
    LET .PLATFORM.ID = SAT.ID(.DTBM.SAT)
ELSE
    FOR EVERY .AM IN FL.MUNITION.SET(.DTBM.FLT)
        WITH (AM.FUNCTION(.AM) = ..LASER
            OR AM.FUNCTION(.AM) = ..KKV)
            AND AM.RNDS.REMAINING(.AM) > 0
        FIND THE FIRST CASE
        IF NONE
            TRACE
            STOP
        OTHERWISE
            LET .TAM = AM.TYPE(.AM)
            LET .DWP = TAM.DTBM.WEAPON(.TAM)
            LET .PLATFORM.ID = FG.ID(.DTBM.FG)
ALWAYS

''determine TBM flight phase (and pK) at which to adjudicate
IF .DTBM.WPN.TYPE = ..AIRBORNE.LASER
    OR .DTBM.WPN.TYPE = ..SPACE.BASED.LASER

    CALL UTL.720.CALCULATE.USER.FUNCTION
        GIVEN
            DWP.SHOT.DURATION.FN(.DWP),
            RN.STREAM(..AIR070.1)
        YIELDING
            .SHOT.DURATION.SEC

    LET .SHOT.DURATION.SEC = MAX.F(.SHOT.DURATION.SEC, 0.0)
    LET .TOTAL.ELAPSED.SECONDS
        = .DETECT.SECONDS.DELAY + .SHOT.DURATION.SEC
    LET .INTERCEPT.FLAG = ..YES

ELSE
    IF .DTBM.WPN.TYPE <> ..KKV

```

```

TRACE
STOP
OTHERWISE

LET .DTBM.X = FG.X.COORD(.DTBM.FG)
LET .DTBM.Y = FG.Y.COORD(.DTBM.FG)
LET .DTBM.Z = PTH.ALTITUDE(FG.CURR.PATH(.DTBM.FG))

CALL AIR.071.COMPUTE.KKV.INTERCEPT.TIME
GIVEN
    .TTT,                ''INDEX OF TBM.TARGET.TYPE
    .TBM.LAUNCH.X,
    .TBM.LAUNCH.Y,
    .TBM.TGT.X,
    .TBM.TGT.Y,
    .DWP,                ''INDEX OF DTBM.WEAPON
    .DTBM.X,
    .DTBM.Y,
    .DTBM.Z,
    .DETECT.SECONDS.DELAY ''FROM TBM LAUNCH TO KKV LAUNCH
YIELDING
    .INTERCEPT.FLAG,  ''..YES OR ..NO SUCCESSFUL INTERCEPT
    .TOTAL.ELAPSED.SECONDS ''FROM TBM LAUNCH TO KKV INTERCEPT
ALWAYS

IF .INTERCEPT.FLAG = ..YES
FOR EVERY TBM.FLIGHT.PHASE CALLED .TFP
DO
    ADD TPT.DURATION.SEC(.TFP, .TTT) TO .SUM.SECONDS
    IF .TOTAL.ELAPSED.SECONDS <= .SUM.SECONDS
        LEAVE
    OTHERWISE
LOOP

IF .TFP > N.TBM.FLIGHT.PHASE
    LET .PK = 0.0
ELSE
    LET .PK = DPT.PK(.DWP, .TFP, .TTT)
ALWAYS
ELSE ''KKV failed to intercept
    LET .PK = 0.0
ALWAYS

''determine result of shot
IF .PK > 0.0
    AND RANDOM.F(RN.STREAM(..AIR070.2)) <= .PK
    LET .NUM.KILLED = 1
ELSE
    LET .NUM.KILLED = 0
ALWAYS

IF (DT.PRINT.FLAG(..AIRF) >= ..LV3 AND
    DT.START.TIME(..AIRF) <= TIME.V <= DT.STOP.TIME(..AIRF))

```

```

OR (DT.PRINT.FLAG(..BPIPP) > ..LV0 AND
DT.START.TIME(..BPIPP) <= TIME.V <= DT.STOP.TIME(..BPIPP))
''Result of DTBM engagement with a TBM
WRITE TIME.V,
    TBU.ID(.TBU),
    FG.ID(FL.FLT.GP(.TBM.FLT)),
    TA.ID(.TBM.TAC),
    .PLATFORM.ID,
    DWP.ID(.DWP),
    .TOTAL.ELAPSED.SECONDS,
    .INTERCEPT.FLAG,
    .PK,
    .NUM.KILLED
AS D(8,4), " AIR070013 ", I 5, S 1, I 7, S 1, I 5, S 1, I 7, S 1,
    S 1, I 5, S 1, D(6,1), S 1, I 1, S 1, D(5,3), S 1, I 1, /
ALWAYS

''expend weapon
IF .DTBM.WPN.TYPE = ..SPACE.BASED.LASER
    SUBTRACT 1 FROM SAT.SPACE.WPN.SHOTS.REMAINING(.DTBM.SAT)

    IF SAT.SPACE.WPN.SHOTS.REMAINING(.DTBM.SAT) < 0
        TRACE
        STOP
    OTHERWISE
ELSE
IF DT.PRINT.FLAG(..DB.EXEC) >= ..LV1 AND
DT.START.TIME(..DB.EXEC) <= TIME.V <= DT.STOP.TIME(..DB.EXEC)
    CALL DBS.220.BEGIN.AIR.TO.AIR.ENGAGEMENT
    GIVEN
        .DTBM.X,
        .DTBM.Y
ALWAYS

SUBTRACT 1 FROM AM.RNDS.REMAINING(.AM)
LET .TMI = TAM.INSTANCE(.TAM)
LET .EXPENDED = TAM.NUMBER(.TAM)

IF TMI.CRITICAL.RESOURCE(TAM.INSTANCE(.TAM)) > 0
    SUBTRACT .EXPENDED FROM TCR.LOADED(TMI.CRITICAL.RESOURCE(.TMI))
    ADD .EXPENDED TO TCR.EXPENDED(TMI.CRITICAL.RESOURCE(.TMI))
ALWAYS

IF DT.PRINT.FLAG(..DB.EXEC) >= ..LV1 AND
DT.START.TIME(..DB.EXEC) <= TIME.V <= DT.STOP.TIME(..DB.EXEC)
    CALL DBS.222.MUNITION.EXPEND.AIR.TO.AIR
    GIVEN
        .DTBM.FLT,
        .DTBM.FG,
        .TMI,
        .EXPENDED
ALWAYS

IF DT.PRINT.FLAG(..GRAPHER2K) >= ..LV1 AND
DT.START.TIME(..GRAPHER2K) <= TIME.V <=

```

```

DT.STOP.TIME(..GRAPHER2K)

CALL GRA.730.AIR.MUNITION.EXPENDITURE
  GIVEN
    ..AA.MUNT.LAUNCHED, 'expenditure type
    .DTBM.FLT,
    .TAM,
    1,           '# of munt sticks
    0,           'not used here
    0,           'not used here
    0,           'not used here
    0           'not used here
  ALWAYS

IF DT.PRINT.FLAG(..GRAPHER2K) >= ..LV1 AND
  DT.START.TIME(..GRAPHER2K) <= TIME.V <=
  DT.STOP.TIME(..GRAPHER2K)

  IF .NUM.KILLED > 0
    CALL GRA.740.AIR.TO.AIR.KILLS
      GIVEN
        .TBM.FLT,           'victim flight
        .DTBM.FLT,        'killer flight
        .NUM.KILLED       'losses to victim flight
      ALWAYS
    ALWAYS

  'set up DTBM flight group statistics for air reports
  IF FG.MSN.STAT(.DTBM.FG) <> 0
    TRACE
    STOP
  OTHERWISE

  CREATE MISSION.STATISTIC CALLED .MS
  LET MS.FLIGHT.GROUP.ID(.MS) = FG.ID(.DTBM.FG)
  LET MS.TIME(.MS) = TIME.V
  LET MS.TARGET.TYPE(.MS) = ..INTERCEPT.POINT
  LET MS.TARGET.ID(.MS) = FG.ID(.TBM.FG)
  LET MS.TARGET.NAME(.MS) = ""
  LET MS.KILLS(.MS) = .NUM.KILLED
  LET FG.MSN.STAT(.DTBM.FG) = .MS

  CREATE FLIGHT.STAT CALLED .FS
  LET FLS.FLIGHT.ID(.FS) = FL.ID(.DTBM.FLT)
  LET FLS.TYPE.AC(.FS) = FL.TYPE.AC(.DTBM.FLT)
  LET FLS.NUM.AC(.FS) = FL.NUM.AC(.DTBM.FLT)
  LET FLS.LOSSES(.FS) = 0
  FILE .FS IN MS.FLIGHT.STAT.SET(.MS)

  CREATE TARGET.COMPONENT.STAT CALLED .TCS
  LET TCS.TYPE.COMPONENT(.TCS) = FL.TYPE.AC(.TBM.FLT)
  LET TCS.COMPONENT.ID(.TCS) = FL.ID(.TBM.FLT)
  LET TCS.QTY.PCT.KILLED(.TCS) = .NUM.KILLED
  FILE .TCS IN MS.TARGET.COMPONENT.SET(.MS)

```

```

CREATE AIR.MUNITION.STAT CALLED .AMS
LET AMS.TYPE(.AMS) = .TAM
LET AMS.LAUNCHES(.AMS) = 1
LET AMS.TGT.TYPE.COMPONENT(.AMS) = ..AIRCRAFT
LET AMS.TGT.COMPONENT.ID(.AMS) = FL.TYPE.AC(.TBM.FLT)
FILE .AMS IN FLS.MUNITION.SET(.FS)

IF FG.MSN.STAT(.TBM.FG) = 0
    CREATE A MISSION.STATISTIC CALLED .MS
    LET FG.MSN.STAT(.TBM.FG) = .MS
ELSE
    LET .MS = FG.MSN.STAT(.TBM.FG)
ALWAYS

LET MS.FLIGHT.GROUP.ID(.MS) = FG.ID(.TBM.FG)
LET MS.TIME(.MS) = TIME.V
LET MS.TARGET.TYPE(.MS) = ..INTERCEPT.POINT
LET MS.TARGET.ID(.MS) = FG.ID(.DTBM.FG)
LET MS.TARGET.NAME(.MS) = ""
LET MS.KILLS(.MS) = 0

CREATE FLIGHT.STAT CALLED .FS
LET FLS.FLIGHT.ID(.FS) = FL.ID(.TBM.FLT)
LET FLS.TYPE.AC(.FS) = FL.TYPE.AC(.TBM.FLT)
LET FLS.NUM.AC(.FS) = FL.NUM.AC(.TBM.FLT)
LET FLS.LOSSES(.FS) = .NUM.KILLED
FILE .FS IN MS.FLIGHT.STAT.SET(.MS)

CREATE TARGET.COMPONENT.STAT CALLED .TCS
LET TCS.TYPE.COMPONENT(.TCS) = FL.TYPE.AC(.DTBM.FLT)
LET TCS.COMPONENT.ID(.TCS) = FL.ID(.DTBM.FLT)
LET TCS.QTY.PCT.KILLED(.TCS) = 0
FILE .TCS IN MS.TARGET.COMPONENT.SET(.MS)

IF DT.PRINT.FLAG(..AA.ENC) >= ..LV1 AND
DT.START.TIME(..AA.ENC) <= TIME.V <= DT.STOP.TIME(..AA.ENC)
    CALL UTL.503.LOCATE.SECTOR.FLOT.X
        GIVEN
            .TBM.LAUNCH.X,
            .TBM.LAUNCH.Y,
            ..BLUE
        YIELDING
            .FLOT.X

    LET .BLUE.DIST.TO.FLOT = .TBM.LAUNCH.X - .FLOT.X

    CALL UTL.503.LOCATE.SECTOR.FLOT.X
        GIVEN
            .TBM.LAUNCH.X,
            .TBM.LAUNCH.Y,
            ..RED
        YIELDING
            .FLOT.X

    LET .RED.DIST.TO.FLOT = .FLOT.X - .TBM.LAUNCH.X

```



```

''Number of flights in the air engagement and the distance
''from the sector FLOT for each side
WRITE TIME.V,
    1,                                ''blue flight
    .BLUE.DIST.TO.FLOT,
    1,                                ''red flight
    .RED.DIST.TO.FLOT
    AS D(8,4), " AIR070091 ", I 3, S 1, I 9, S 1, I 3, S 1, I 9, /

''Describes a DTBM flight in an air engagement.
WRITE TIME.V,
    TA.USED.INDEX(FL.TYPE.AC(.DTBM.FLT)),
    FL.MISSION(.DTBM.FLT),
    FL.NUM.AC(.DTBM.FLT),
    FG.STATUS(FL.FLT.GP(.DTBM.FLT))
    AS D(8,4), " AIR070101 ", I 5, S 1, I 5, S 1, I 5, S 1, I 5, /

''Describes a TBM flight in an air engagement.
WRITE TIME.V,
    TA.USED.INDEX(FL.TYPE.AC(.TBM.FLT)),
    FL.MISSION(.TBM.FLT),
    FL.NUM.AC(.TBM.FLT),
    FG.STATUS(FL.FLT.GP(.TBM.FLT))
    AS D(8,4), " AIR070101 ", I 5, S 1, I 5, S 1, I 5, S 1, I 5, /
ALWAYS

IF DT.PRINT.FLAG(..AA.KILLS) >= ..LV1 AND
DT.START.TIME(..AA.KILLS) <= TIME.V <= DT.STOP.TIME(..AA.KILLS)
''Air-to-Air kills for post processor
WRITE TIME.V,
    TA.USED.INDEX(FL.TYPE.AC(.DTBM.FLT)),
    FL.MISSION(.DTBM.FLT),
    FL.NUM.AC(.DTBM.FLT),
    TA.USED.INDEX(FL.TYPE.AC(.TBM.FLT)),
    FL.MISSION(.TBM.FLT),
    FL.NUM.AC(.TBM.FLT),
    0                                ''num lost by DTBM
    AS D(8,4), " AIR070081", S 1, I 5, S 1, I 5, S 1,
    I 5, S 1, I 5, S 1, I 5, S 1, I 5, S 1, I 5, /

''Air-to-Air kills for post processor
WRITE TIME.V,
    TA.USED.INDEX(FL.TYPE.AC(.TBM.FLT)),
    FL.MISSION(.TBM.FLT),
    FL.NUM.AC(.TBM.FLT),
    TA.USED.INDEX(FL.TYPE.AC(.DTBM.FLT)),
    FL.MISSION(.DTBM.FLT),
    FL.NUM.AC(.DTBM.FLT),
    .NUM.KILLED
    AS D(8,4), " AIR070081", S 1, I 5, S 1, I 5, S 1,
    I 5, S 1, I 5, S 1, I 5, S 1, I 5, S 1, I 5, /
ALWAYS

''report results

```

```

CALL UTL.270.MISSION.STAT.REPORT
  GIVEN
    .DTBM.FG,
    ..DTBM

CALL UTL.270.MISSION.STAT.REPORT
  GIVEN
    .TBM.FG,
    ..ALL.FLIGHTS
ALWAYS

IF .NUM.KILLED = 1
  IF .DTBM.WPN.TYPE <> ..SPACE.BASED.LASER
    IF DT.PRINT.FLAG(..DB.EXEC) >= ..LV1 AND
      DT.START.TIME(..DB.EXEC) <= TIME.V <=
      DT.STOP.TIME(..DB.EXEC)
      CALL DBS.221.FLT.LOSS.AIR.TO.AIR
        GIVEN
          .TBM.FLT,
          .TBM.FG,
          1,                                ''loss
          ..YES,                            ''before target
          TA.ID(.TBM.TAC),
          FL.MISSION(.TBM.FLT)
    ALWAYS

  IF (POST.PROCESS.GRAPHICS = ..MAP OR
      POST.PROCESS.GRAPHICS = ..BOTH) AND
      DT.PRINT.FLAG(..GRAA) GE ..LV2 AND
      DT.START.TIME(..GRAA) LE TIME.V LE DT.STOP.TIME(..GRAA)

    IF FG.SIDE(.DTBM.FG) = ..BLUE
      LET .BLUE.FG = .DTBM.FG
      LET .RED.FG = .TBM.FG
    ELSE
      LET .BLUE.FG = .TBM.FG
      LET .RED.FG = .DTBM.FG
    ALWAYS

    ''FOR NOW
    LET .ENGAGE.X = .5 * (.TBM.LAUNCH.X + .TBM.TGT.X)
    LET .ENGAGE.Y = .5 * (.TBM.LAUNCH.Y + .TBM.TGT.Y)

    LET .SAVE.TBM.X = FG.X.COORD(.TBM.FG)
    LET .SAVE.TBM.Y = FG.Y.COORD(.TBM.FG)
    LET FG.X.COORD(.TBM.FG) = .ENGAGE.X
    LET FG.Y.COORD(.TBM.FG) = .ENGAGE.Y

    IF DT.PRINT.FLAG(..GRAA) >= ..LV3
      LET FG.CURR.PATH(.TBM.FG) = F.FG.PATH.SET(.TBM.FG)

    CALL GRA.600.PRINT.MISSION.MOVE.EVENT
      GIVEN
        .TBM.FG,

```

```

        .TBM.FLT

        LET FG.CURR.PATH(.TBM.FG) = 0
    ALWAYS

    LET FL.NUM.AC.LOST.LAST.ATTACK(.TBM.FLT) = .NUM.KILLED
    LET FL.ENGAGE.FLAG(.TBM.FLT) = ..YES
    LET FL.ENGAGE.FLAG(.DTBM.FLT) = ..YES

    ''TEMPORARILY MOVE DTBM FLIGHT GROUP SO GRAPHICS WILL SHOW
    '' ENGAGEMENT ALONG TBM FLIGHT PATH
    LET .SAVE.DTBM.X = FG.X.COORD(.DTBM.FG)
    LET .SAVE.DTBM.Y = FG.Y.COORD(.DTBM.FG)
    LET FG.X.COORD(.DTBM.FG) = .ENGAGE.X
    LET FG.Y.COORD(.DTBM.FG) = .ENGAGE.Y

    CALL GRA.540.AIR.TO.AIR.LOSS
        GIVING
            .BLUE.FG,
            .RED.FG

    LET FG.X.COORD(.DTBM.FG) = .SAVE.DTBM.X
    LET FG.Y.COORD(.DTBM.FG) = .SAVE.DTBM.Y
    LET FG.X.COORD(.TBM.FG) = .SAVE.TBM.X
    LET FG.Y.COORD(.TBM.FG) = .SAVE.TBM.Y

    LET FL.NUM.AC.LOST.LAST.ATTACK(.TBM.FLT) = 0
    LET FL.ENGAGE.FLAG(.TBM.FLT) = ..NO
    LET FL.ENGAGE.FLAG(.DTBM.FLT) = ..NO
    ALWAYS
ALWAYS

''clean up tbm flight & flight group
CALL UTL.090.DESTROY.AIRCRAFT
    GIVEN
        .TBM.FLT,
        .NUM.KILLED,
        ..AIRCRAFT

CALL AIR.510.DECISION.POINT
    GIVEN
        .TBM.FG,
        ..YES      ''aircraft lost
    YIELDING
        .CONTINUE

IF .CONTINUE <> ..NO
    TRACE
    STOP
OTHERWISE

FOR EVERY .EVENT4 IN EV.S(I.AIR.004.MOVE.FLT.GP)
    WITH MFG.FLT.GP(.EVENT4) = .TBM.FG
FIND THE FIRST CASE

```

```

IF NONE
  TRACE
  STOP
  OTHERWISE

  CANCEL AIR.004.MOVE.FLT.GP CALLED .EVENT4
  DESTROY AIR.004.MOVE.FLT.GP CALLED .EVENT4
  ALWAYS

IF .DTBM.WPN.TYPE <> ..SPACE.BASED.LASER

  IF DT.PRINT.FLAG(..DB.EXEC) >= ..LV1 AND
    DT.START.TIME(..DB.EXEC) <= TIME.V <= DT.STOP.TIME(..DB.EXEC)
    CALL DBS.229.END.AIR.TO.AIR.ENGAGEMENT
  ALWAYS

  ''continuation decision of no will cause DTBM to leave station
  CALL AIR.510.DECISION.POINT
  GIVEN
    .DTBM.FG,
    ..NO      ''aircraft lost
  YIELDING
    .CONTINUE
  ALWAYS

  EXITROUTINE
ENDROUTINE

```

Appendix F: Example SIMSCRIPT II.5 Code AIR070.SIM (Modified)

```
ROUTINE AIR.070.ADJUDICATE.DTBM
  '$Id: air070.sim,v 2.10 2000/09/20 20:12:38 steveh Exp $

GIVEN
  .DTBM.PLATFORM,      ''PTR TO DTBM PLATFORM FIRING AT TBM
  .DTBM.WPN.TYPE,      ''TYPE OF SHOOTER ENGAGING TBM
  .TBU,                ''INDEX OF TBM.UNIT LAUNCHING TBM
  .TBM.FLT,            ''POINTER TO TBM FLIGHT BEING LAUNCHED
  .DETECT.SECONDS.DELAY ''BETWEEN TBM LAUNCH AND DTBM RESPONSE

''YIELDING
''  NONE

''PURPOSE
''-----
''  ADJUDICATE A DTBM VS. TBM AIR-TO-AIR ENGAGEMENT

''PROCESSING
''-----
''

''=====
''CALLED BY
''-----
''  AIR.060.BOOST.PHASE.INTERCEPT.MANAGER

''CHANGE LOG
''-----
''  DATE          AUTHOR          CHANGE SUMMARY
''-----
''  1-11-96       MORGAN          INITIAL IMPLEMENTATION
''  1-23-96       EMERT           REPLACED .TBT WITH .TTT
''  2-6-96        MORGAN          SET FL.ENGAGE.FLAG
''  2-9-96        MORGAN          DISPLAY ENGAGEMENTS ALONG TBM PATH
''  6-12-96       MORGAN          MAKE LASER SHOT TIME A DISTRIBUTION
''  8-09-99       HADLEY          FLIGHT GROUP MISSION STATS MAY HAVE
''                BEEN CREATED EARLIER
''  08-16-99      LENNOX          CALL GRA.730, GRA.740 FOR GRAPHER2K
''  2-11-00       COSGROVE        ADD SBL
''  07-10-00      HADLEY          UP FLIGHT GROUP ID IN TRANS TO I 7
''=====

NORMALLY MODE IS INTEGER
DEFINE .DETECT.SECONDS.DELAY, .PK, .SHOT.DURATION.SEC, .SUM.SECONDS,
      .TOTAL.ELAPSED.SECONDS
      AS DOUBLE VARIABLES

IF .DTBM.WPN.TYPE = ..SPACE.BASED.LASER
  LET .DTBM.SAT = .DTBM.PLATFORM
ELSE
```

```

LET .DTBM.FG = .DTBM.PLATFORM

LET .DTBM.FLT = F.FG.FLIGHT.SET(.DTBM.FG)
IF FL.MISSION(.DTBM.FLT) <> ..DTBM
    TRACE
    STOP
    OTHERWISE
ALWAYS

LET .TBM.FG = FL.FLT.GP(.TBM.FLT)
LET .TBM.LAUNCH.X = TBU.X.COORD(.TBU)
LET .TBM.LAUNCH.Y = TBU.Y.COORD(.TBU)
LET .TBM.TAC = TBU.TYPE.AC(.TBU)
LET .TTT = TA.TBM.TARGET.TYPE(.TBM.TAC)
LET .TBM.TGT = FG.TARGET(.TBM.FG)
LET .TBM.TGT.X = TG.X.COORD(.TBM.TGT)
LET .TBM.TGT.Y = TG.Y.COORD(.TBM.TGT)

IF .DTBM.WPN.TYPE = ..SPACE.BASED.LASER
    LET .TSW = SAT.TYPE.SPACE.WPN(.DTBM.SAT)
    LET .DWP = TSW.DTBM.WEAPON(.TSW)
    LET .PLATFORM.ID = SAT.ID(.DTBM.SAT)
ELSE
    FOR EVERY .AM IN FL.MUNITION.SET(.DTBM.FLT)
        WITH (AM.FUNCTION(.AM) = ..LASER
            OR AM.FUNCTION(.AM) = ..KKV)
            AND AM.RNDS.REMAINING(.AM) > 0
        FIND THE FIRST CASE
        IF NONE
            TRACE
            STOP
        OTHERWISE
            LET .TAM = AM.TYPE(.AM)
            LET .DWP = TAM.DTBM.WEAPON(.TAM)
            LET .PLATFORM.ID = FG.ID(.DTBM.FG)
ALWAYS

''determine TBM flight phase (and pK) at which to adjudicate
IF .DTBM.WPN.TYPE = ..AIRBORNE.LASER
    OR .DTBM.WPN.TYPE = ..SPACE.BASED.LASER

    CALL UTL.720.CALCULATE.USER.FUNCTION
        GIVEN
            DWP.SHOT.DURATION.FN(.DWP),
            RN.STREAM(..AIR070.1)
        YIELDING
            .SHOT.DURATION.SEC

*****
''*   Earl stuff   *
*****

EARL.RESPONSE = .SHOT.DURATION.SEC
EB.P1 = UF.PARM1(DWP.SHOT.DURATION.FN(.DWP))
EB.P2 = UF.PARM2(DWP.SHOT.DURATION.FN(.DWP))

```

```

EB.P3 = 0.0

CALL EARL.STORE
  GIVEN
    ..AIR070.1,
    UF.FUNCTION(DWP.SHOT.DURATION.FN(.DWP)),
    EARL.RESPONSE,
    EB.P1,
    EB.P2,
    EB.P3

''* END STUFF

LET .SHOT.DURATION.SEC = MAX.F(.SHOT.DURATION.SEC, 0.0)
LET .TOTAL.ELAPSED.SECONDS
  = .DETECT.SECONDS.DELAY + .SHOT.DURATION.SEC
LET .INTERCEPT.FLAG = ..YES

ELSE
  IF .DTBM.WPN.TYPE <> ..KKV
    TRACE
    STOP
  OTHERWISE

LET .DTBM.X = FG.X.COORD(.DTBM.FG)
LET .DTBM.Y = FG.Y.COORD(.DTBM.FG)
LET .DTBM.Z = PTH.ALTITUDE(FG.CURR.PATH(.DTBM.FG))

CALL AIR.071.COMPUTE.KKV.INTERCEPT.TIME
  GIVEN
    .TTT,                'INDEX OF TBM.TARGET.TYPE
    .TBM.LAUNCH.X,
    .TBM.LAUNCH.Y,
    .TBM.TGT.X,
    .TBM.TGT.Y,
    .DWP,                'INDEX OF DTBM.WEAPON
    .DTBM.X,
    .DTBM.Y,
    .DTBM.Z,
    .DETECT.SECONDS.DELAY 'FROM TBM LAUNCH TO KKV LAUNCH
  YIELDING
    .INTERCEPT.FLAG,  ' '..YES OR ..NO SUCCESSFUL INTERCEPT
    .TOTAL.ELAPSED.SECONDS 'FROM TBM LAUNCH TO KKV INTERCEPT
ALWAYS

IF .INTERCEPT.FLAG = ..YES
  FOR EVERY TBM.FLIGHT.PHASE CALLED .TFP
  DO
    ADD TPT.DURATION.SEC(.TFP, .TTT) TO .SUM.SECONDS
    IF .TOTAL.ELAPSED.SECONDS <= .SUM.SECONDS
      LEAVE
    OTHERWISE
  LOOP

IF .TFP > N.TBM.FLIGHT.PHASE

```

```

        LET .PK = 0.0
    ELSE
        LET .PK = DPT.PK(.DWP, .TFP, .TTT)
    ALWAYS
ELSE    ''KKV failed to intercept
    LET .PK = 0.0
ALWAYS

''determine result of shot

''*****
''*   Earl stuff           *
''*****

    EARL.RESPONSE = RANDOM.F(RN.STREAM(..AIR070.2))

    EB.P1 = 0.0
    EB.P2 = 0.0
    EB.P3 = 0.0

    CALL EARL.STORE
        GIVEN
            ..AIR070.2,
            ..RANDOM,
            EARL.RESPONSE,
            EB.P1,
            EB.P2,
            EB.P3

''* END STUFF

    IF .PK > 0.0
        AND EARL.RESPONSE <= .PK
        LET .NUM.KILLED = 1
    ELSE
        LET .NUM.KILLED = 0
    ALWAYS

    IF (DT.PRINT.FLAG(..AIRF) >= ..LV3 AND
        DT.START.TIME(..AIRF) <= TIME.V <= DT.STOP.TIME(..AIRF))
        OR (DT.PRINT.FLAG(..BPIPP) > ..LV0 AND
            DT.START.TIME(..BPIPP) <= TIME.V <= DT.STOP.TIME(..BPIPP))
        ''Result of DTBM engagement with a TBM
        WRITE TIME.V,
            TBU.ID(.TBU),
            FG.ID(FL.FLT.GP(.TBM.FLT)),
            TA.ID(.TBM.TAC),
            .PLATFORM.ID,
            DWP.ID(.DWP),
            .TOTAL.ELAPSED.SECONDS,
            .INTERCEPT.FLAG,
            .PK,
            .NUM.KILLED

```



```

AS D(8,4), " AIR070013 ", I 5, S 1, I 7, S 1, I 5, S 1, I 7, S 1,
S 1, I 5, S 1, D(6,1), S 1, I 1, S 1, D(5,3), S 1, I 1, /
ALWAYS

' 'expend weapon
IF .DTBM.WPN.TYPE = ..SPACE.BASED.LASER
SUBTRACT 1 FROM SAT.SPACE.WPN.SHOTS.REMAINING(.DTBM.SAT)

IF SAT.SPACE.WPN.SHOTS.REMAINING(.DTBM.SAT) < 0
TRACE
STOP
OTHERWISE
ELSE
IF DT.PRINT.FLAG(..DB.EXEC) >= ..LV1 AND
DT.START.TIME(..DB.EXEC) <= TIME.V <= DT.STOP.TIME(..DB.EXEC)
CALL DBS.220.BEGIN.AIR.TO.AIR.ENGAGEMENT
GIVEN
.DTBM.X,
.DTBM.Y
ALWAYS

SUBTRACT 1 FROM AM.RNDS.REMAINING(.AM)
LET .TMI = TAM.INSTANCE(.TAM)
LET .EXPENDED = TAM.NUMBER(.TAM)

IF TMI.CRITICAL.RESOURCE(TAM.INSTANCE(.TAM)) > 0
SUBTRACT .EXPENDED FROM TCR.LOADED(TMI.CRITICAL.RESOURCE(.TMI))
ADD .EXPENDED TO TCR.EXPENDED(TMI.CRITICAL.RESOURCE(.TMI))
ALWAYS

IF DT.PRINT.FLAG(..DB.EXEC) >= ..LV1 AND
DT.START.TIME(..DB.EXEC) <= TIME.V <= DT.STOP.TIME(..DB.EXEC)
CALL DBS.222.MUNITION.EXPEND.AIR.TO.AIR
GIVEN
.DTBM.FLT,
.DTBM.FG,
.TMI,
.EXPENDED
ALWAYS

IF DT.PRINT.FLAG(..GRAPHER2K) >= ..LV1 AND
DT.START.TIME(..GRAPHER2K) <= TIME.V <=
DT.STOP.TIME(..GRAPHER2K)

CALL GRA.730.AIR.MUNITION.EXPENDITURE
GIVEN
..AA.MUNT.LAUNCHED, ' 'expenditure type
.DTBM.FLT,
.TAM,
1, '# of munt sticks
0, ' 'not used here
0, ' 'not used here
0, ' 'not used here
0, ' 'not used here
0, ' 'not used here
ALWAYS

```

```

IF DT.PRINT.FLAG(..GRAPHER2K) >= ..LV1 AND
DT.START.TIME(..GRAPHER2K) <= TIME.V <=
DT.STOP.TIME(..GRAPHER2K)

    IF .NUM.KILLED > 0
        CALL GRA.740.AIR.TO.AIR.KILLS
            GIVEN
                .TBM.FLT,           ''victim flight
                .DTBM.FLT,         ''killer flight
                .NUM.KILLED        ''losses to victim flight
            ALWAYS
        ALWAYS

''set up DTBM flight group statistics for air reports
IF FG.MSN.STAT(.DTBM.FG) <> 0
    TRACE
    STOP
OTHERWISE

CREATE MISSION.STATISTIC CALLED .MS
LET MS.FLIGHT.GROUP.ID(.MS) = FG.ID(.DTBM.FG)
LET MS.TIME(.MS) = TIME.V
LET MS.TARGET.TYPE(.MS) = ..INTERCEPT.POINT
LET MS.TARGET.ID(.MS) = FG.ID(.TBM.FG)
LET MS.TARGET.NAME(.MS) = ""
LET MS.KILLS(.MS) = .NUM.KILLED
LET FG.MSN.STAT(.DTBM.FG) = .MS

CREATE FLIGHT.STAT CALLED .FS
LET FLS.FLIGHT.ID(.FS) = FL.ID(.DTBM.FLT)
LET FLS.TYPE.AC(.FS) = FL.TYPE.AC(.DTBM.FLT)
LET FLS.NUM.AC(.FS) = FL.NUM.AC(.DTBM.FLT)
LET FLS.LOSSES(.FS) = 0
FILE .FS IN MS.FLIGHT.STAT.SET(.MS)

CREATE TARGET.COMPONENT.STAT CALLED .TCS
LET TCS.TYPE.COMPONENT(.TCS) = FL.TYPE.AC(.TBM.FLT)
LET TCS.COMPONENT.ID(.TCS) = FL.ID(.TBM.FLT)
LET TCS.QTY.PCT.KILLED(.TCS) = .NUM.KILLED
FILE .TCS IN MS.TARGET.COMPONENT.SET(.MS)

CREATE AIR.MUNITION.STAT CALLED .AMS
LET AMS.TYPE(.AMS) = .TAM
LET AMS.LAUNCHES(.AMS) = 1
LET AMS.TGT.TYPE.COMPONENT(.AMS) = ..AIRCRAFT
LET AMS.TGT.COMPONENT.ID(.AMS) = FL.TYPE.AC(.TBM.FLT)
FILE .AMS IN FLS.MUNITION.SET(.FS)

IF FG.MSN.STAT(.TBM.FG) = 0
    CREATE A MISSION.STATISTIC CALLED .MS
    LET FG.MSN.STAT(.TBM.FG) = .MS
ELSE
    LET .MS = FG.MSN.STAT(.TBM.FG)
ALWAYS

```

```

LET MS.FLIGHT.GROUP.ID(.MS) = FG.ID(.TBM.FG)
LET MS.TIME(.MS) = TIME.V
LET MS.TARGET.TYPE(.MS) = ..INTERCEPT.POINT
LET MS.TARGET.ID(.MS) = FG.ID(.DTBM.FG)
LET MS.TARGET.NAME(.MS) = ""
LET MS.KILLS(.MS) = 0

CREATE FLIGHT.STAT CALLED .FS
LET FLS.FLIGHT.ID(.FS) = FL.ID(.TBM.FLT)
LET FLS.TYPE.AC(.FS) = FL.TYPE.AC(.TBM.FLT)
LET FLS.NUM.AC(.FS) = FL.NUM.AC(.TBM.FLT)
LET FLS.LOSSES(.FS) = .NUM.KILLED
FILE .FS IN MS.FLIGHT.STAT.SET(.MS)

CREATE TARGET.COMPONENT.STAT CALLED .TCS
LET TCS.TYPE.COMPONENT(.TCS) = FL.TYPE.AC(.DTBM.FLT)
LET TCS.COMPONENT.ID(.TCS) = FL.ID(.DTBM.FLT)
LET TCS.QTY.PCT.KILLED(.TCS) = 0
FILE .TCS IN MS.TARGET.COMPONENT.SET(.MS)

IF DT.PRINT.FLAG(..AA.ENC) >= ..LV1 AND
DT.START.TIME(..AA.ENC) <= TIME.V <= DT.STOP.TIME(..AA.ENC)
CALL UTL.503.LOCATE.SECTOR.FLOT.X
    GIVEN
        .TBM.LAUNCH.X,
        .TBM.LAUNCH.Y,
        ..BLUE
    YIELDING
        .FLOT.X

LET .BLUE.DIST.TO.FLOT = .TBM.LAUNCH.X - .FLOT.X

CALL UTL.503.LOCATE.SECTOR.FLOT.X
    GIVEN
        .TBM.LAUNCH.X,
        .TBM.LAUNCH.Y,
        ..RED
    YIELDING
        .FLOT.X

LET .RED.DIST.TO.FLOT = .FLOT.X - .TBM.LAUNCH.X

''Number of flights in the air engagement and the distance
''from the sector FLOT for each side
WRITE TIME.V,
    1,                                ''blue flight
    .BLUE.DIST.TO.FLOT,
    1,                                ''red flight
    .RED.DIST.TO.FLOT
    AS D(8,4)," AIR070091 ",I 3,S 1,I 9,S 1,I 3,S 1,I 9, /

''Describes a DTBM flight in an air engagement.
WRITE TIME.V,
    TA.USED.INDEX(FL.TYPE.AC(.DTBM.FLT)),

```

```

        FL.MISSION(.DTBM.FLT),
        FL.NUM.AC(.DTBM.FLT),
        FG.STATUS(FL.FLT.GP(.DTBM.FLT))
    AS D(8,4), " AIR070101 ", I 5, S 1, I 5, S 1, I 5, S 1, I 5, /

    'Describes a TBM flight in an air engagement.
WRITE TIME.V,
    TA.USED.INDEX(FL.TYPE.AC(.TBM.FLT)),
    FL.MISSION(.TBM.FLT),
    FL.NUM.AC(.TBM.FLT),
    FG.STATUS(FL.FLT.GP(.TBM.FLT))
    AS D(8,4), " AIR070101 ", I 5, S 1, I 5, S 1, I 5, S 1, I 5, /
ALWAYS

IF DT.PRINT.FLAG(..AA.KILLS) >= ..LV1 AND
DT.START.TIME(..AA.KILLS) <= TIME.V <= DT.STOP.TIME(..AA.KILLS)
    'Air-to-Air kills for post processor
WRITE TIME.V,
    TA.USED.INDEX(FL.TYPE.AC(.DTBM.FLT)),
    FL.MISSION(.DTBM.FLT),
    FL.NUM.AC(.DTBM.FLT),
    TA.USED.INDEX(FL.TYPE.AC(.TBM.FLT)),
    FL.MISSION(.TBM.FLT),
    FL.NUM.AC(.TBM.FLT),
    0                                'num lost by DTBM
    AS D(8,4), " AIR070081", S 1, I 5, S 1, I 5, S 1,
    I 5, S 1, I 5, S 1, I 5, S 1, I 5, S 1, I 5, /

    'Air-to-Air kills for post processor
WRITE TIME.V,
    TA.USED.INDEX(FL.TYPE.AC(.TBM.FLT)),
    FL.MISSION(.TBM.FLT),
    FL.NUM.AC(.TBM.FLT),
    TA.USED.INDEX(FL.TYPE.AC(.DTBM.FLT)),
    FL.MISSION(.DTBM.FLT),
    FL.NUM.AC(.DTBM.FLT),
    .NUM.KILLED
    AS D(8,4), " AIR070081", S 1, I 5, S 1, I 5, S 1,
    I 5, S 1, I 5, S 1, I 5, S 1, I 5, S 1, I 5, /
ALWAYS

    'report results
CALL UTL.270.MISSION.STAT.REPORT
    GIVEN
        .DTBM.FG,
        ..DTBM

CALL UTL.270.MISSION.STAT.REPORT
    GIVEN
        .TBM.FG,
        ..ALL.FLIGHTS
ALWAYS

IF .NUM.KILLED = 1

```

```

IF .DTBM.WPN.TYPE <> ..SPACE.BASED.LASER
IF DT.PRINT.FLAG(..DB.EXEC) >= ..LV1 AND
DT.START.TIME(..DB.EXEC) <= TIME.V <=
DT.STOP.TIME(..DB.EXEC)
CALL DBS.221.FLT.LOSS.AIR.TO.AIR
    GIVEN
        .TBM.FLT,
        .TBM.FG,
        1,                ''loss
        ..YES,            ''before target
        TA.ID(.TBM.TAC),
        FL.MISSION(.TBM.FLT)
ALWAYS

IF (POST.PROCESS.GRAPHICS = ..MAP OR
    POST.PROCESS.GRAPHICS = ..BOTH) AND
DT.PRINT.FLAG(..GRAA) GE ..LV2 AND
DT.START.TIME(..GRAA) LE TIME.V LE DT.STOP.TIME(..GRAA)

IF FG.SIDE(.DTBM.FG) = ..BLUE
    LET .BLUE.FG = .DTBM.FG
    LET .RED.FG = .TBM.FG
ELSE
    LET .BLUE.FG = .TBM.FG
    LET .RED.FG = .DTBM.FG
ALWAYS

''FOR NOW
LET .ENGAGE.X = .5 * (.TBM.LAUNCH.X + .TBM.TGT.X)
LET .ENGAGE.Y = .5 * (.TBM.LAUNCH.Y + .TBM.TGT.Y)

LET .SAVE.TBM.X = FG.X.COORD(.TBM.FG)
LET .SAVE.TBM.Y = FG.Y.COORD(.TBM.FG)
LET FG.X.COORD(.TBM.FG) = .ENGAGE.X
LET FG.Y.COORD(.TBM.FG) = .ENGAGE.Y

IF DT.PRINT.FLAG(..GRAA) >= ..LV3
    LET FG.CURR.PATH(.TBM.FG) = F.FG.PATH.SET(.TBM.FG)

    CALL GRA.600.PRINT.MISSION.MOVE.EVENT
        GIVEN
            .TBM.FG,
            .TBM.FLT

    LET FG.CURR.PATH(.TBM.FG) = 0
ALWAYS

LET FL.NUM.AC.LOST.LAST.ATTACK(.TBM.FLT) = .NUM.KILLED
LET FL.ENGAGE.FLAG(.TBM.FLT) = ..YES
LET FL.ENGAGE.FLAG(.DTBM.FLT) = ..YES

''TEMPORARILY MOVE DTBM FLIGHT GROUP SO GRAPHICS WILL SHOW
'' ENGAGEMENT ALONG TBM FLIGHT PATH
LET .SAVE.DTBM.X = FG.X.COORD(.DTBM.FG)
LET .SAVE.DTBM.Y = FG.Y.COORD(.DTBM.FG)

```

```

LET FG.X.COORD(.DTBM.FG) = .ENGAGE.X
LET FG.Y.COORD(.DTBM.FG) = .ENGAGE.Y

CALL GRA.540.AIR.TO.AIR.LOSS
  GIVING
    .BLUE.FG,
    .RED.FG

LET FG.X.COORD(.DTBM.FG) = .SAVE.DTBM.X
LET FG.Y.COORD(.DTBM.FG) = .SAVE.DTBM.Y
LET FG.X.COORD(.TBM.FG) = .SAVE.TBM.X
LET FG.Y.COORD(.TBM.FG) = .SAVE.TBM.Y

LET FL.NUM.AC.LOST.LAST.ATTACK(.TBM.FLT) = 0
LET FL.ENGAGE.FLAG(.TBM.FLT) = ..NO
LET FL.ENGAGE.FLAG(.DTBM.FLT) = ..NO
  ALWAYS
ALWAYS

''clean up tbm flight & flight group
CALL UTL.090.DESTROY.AIRCRAFT
  GIVEN
    .TBM.FLT,
    .NUM.KILLED,
    ..AIRCRAFT

CALL AIR.510.DECISION.POINT
  GIVEN
    .TBM.FG,
    ..YES      ''aircraft lost
  YIELDING
    .CONTINUE

IF .CONTINUE <> ..NO
  TRACE
  STOP
OTHERWISE

FOR EVERY .EVENT4 IN EV.S(I.AIR.004.MOVE.FLT.GP)
  WITH MFG.FLT.GP(.EVENT4) = .TBM.FG
  FIND THE FIRST CASE
  IF NONE
    TRACE
    STOP
  OTHERWISE

  CANCEL AIR.004.MOVE.FLT.GP CALLED .EVENT4
  DESTROY AIR.004.MOVE.FLT.GP CALLED .EVENT4
ALWAYS

IF .DTBM.WPN.TYPE <> ..SPACE.BASED.LASER

```

```
IF DT.PRINT.FLAG(..DB.EXEC) >= ..LV1 AND
  DT.START.TIME(..DB.EXEC) <= TIME.V <= DT.STOP.TIME(..DB.EXEC)
  CALL DBS.229.END.AIR.TO.AIR.ENGAGEMENT
ALWAYS

''continuation decision of no will cause DTBM to leave station
CALL AIR.510.DECISION.POINT
  GIVEN
    .DTBM.FG,
    ..NO      ''aircraft lost
  YIELDING
    .CONTINUE
ALWAYS

EXITROUTINE
ENDROUTINE
```

Appendix G: MRG32k3a Routines and Variables (18)

Routines:

RngStream (const char *name = "");

This constructor creates a new stream with (optional) descriptor name. It initializes its seed Ig , and sets Bg and Cg to Ig . It also sets its `anti` and `incPrec` switches to false. The seed Ig is equal to the initial seed of the package if this is the first stream created; otherwise it is Z steps ahead of the seed of the most recently created stream.

void SetPackageSeed (const unsigned long seed[6]);

Sets the initial seed s_0 of the package to the six integers in the vector `seed`. The first 3 integers in the seed must all be less than $m_1 = 4294967087$, and not all 0; and the last 3 integers must all be less than $m_2 = 4294944443$, and not all 0. If this method is not called, the default initial seed is (12345, 12345, 12345, 12345, 12345, 12345).

void ResetStartStream ();

Reinitializes the stream to its initial state: Cg and Bg are set to Ig .

void ResetStartSubstream ();

Reinitializes the stream to the beginning of its current substream: Cg is set to Bg .

void ResetNextSubstream ();

Reinitializes the stream to the beginning of its next substream: Ng is computed, and Cg and Bg are set to Ng .

void SetAntithetic (bool a);

If $a = \text{true}$, the stream will start generating antithetic variates, i.e., $1 - U$ instead of U , until this method is called again with $a = \text{false}$.

void IncreasedPrecis (bool incp);

After calling this method with `incp = true`, each call to the generator (direct or indirect) for this stream will return a uniform random number with more bits of resolution (53 bits if machine follows IEEE 754 standard) instead of 32 bits, and will advance the state of the stream by 2 steps instead of 1. More precisely, if s is a stream of the class `RngStream`, in the nonantithetic case, the instruction “`u = s.RandU01()`” will be equivalent to “`u = (s.RandU01() + s.RandU01() * fact) % 1.0`” where the constant `fact` is equal to 2^{-24} . This also applies when calling `RandU01` indirectly (e.g., via `RandInt`, etc.). By default, or if this method is called again with `incp = false`, each call to `RandU01` for this stream advances the state by 1 step and returns a number with 32 bits of resolution.

void SetSeed (const unsigned long seed[6]);

Sets the initial seed Ig of the stream to the vector `seed`. The vector `seed` should contain

valid seed values as described in `SetPackageSeed`. The state of the stream is then reset to this initial seed. The states and seeds of the other streams are not modified. As a result, after calling this method, the initial seeds of the streams are no longer spaced Z values apart. We discourage the use of this method; proper use of the `Reset*` methods is preferable.

`void AdvanceState (long e, long c);`

Advances the state by n steps (see below for the meaning of n), without modifying the states of other streams or the values of `Bg` and `Ig` in the current object. If $e > 0$, then $n = 2e + c$; if $e < 0$, then $n = -2-e + c$; and if $e = 0$, then $n = c$. Note: c is allowed to take negative values. We discourage the use of this method.

`void GetState (unsigned long seed[6]) const;`

Returns in `seed[0..5]` the current state `Cg` of this stream. This is convenient if we want to save the state for subsequent use.

`void WriteState () const;`

Writes (to standard output) the current state `Cg` of this stream.

`void WriteStateFull () const;`

Writes (to standard output) the value of all the internal variables of this stream: `name`, `anti`, `incPrec`, `Ig`, `Bg`, `Cg`.

`double RandU01 ();`

Normally, returns a (pseudo)random number from the uniform distribution over the interval $(0, 1)$, after advancing the state by one step. The returned number has 32 bits of precision in the sense that it is always a multiple of $1/(2^{32}-208)$. However, if `IncreasedPrecis(true)` has been called for this stream, the state is advanced by two steps and the returned number has bits of precision.

`long RandInt (long i, long j);`

Returns a (pseudo)random number from the discrete uniform distribution over the integers $\{i, i + 1, \dots, j\}$. Makes one call to `RandU01`.

Variables:

`double Cg[6], Bg[6], Ig[6];`

Vectors to store the current seed, the beginning of the current block (substream) and the beginning of the current stream.

`bool anti, incPrec;`

Variables to indicate whether to generate antithetic or increased precision random numbers.

`std::string name;`

String to store the optional name of the current `RngStream` object.

`static double nextSeed[6];`

Static vector to store the beginning state of the next `RngStream` to be created (instantiated).

`double U01 ();`

The backbone uniform random number generator.

`double U01d ();`

The backbone uniform random number generator with increased precision.

Appendix H: CHARACTERISTICS OF VRTs (6)

CHARACTERISTICS OF VARIANCE REDUCTION TECHNIQUES					
VRT	DESCRIPTION OF TECHNIQUE	CRITERIA OF APPLICATION	ADVANTAGES	DISADVANTAGES	TYPICAL APPLICATIONS
Importance Sampling	Sample procedure is modified such that the more important events are sampled more frequently	<p>Certain events are known to be important</p> <p>Estimated parameters are based on events with low probability of occurrence</p> <p>Certain events are not of interest</p> <p>Regions of importance can be defined</p>	<p>It can give great improvement with limited effort</p> <p>Well developed procedures</p> <p>Easy implementation</p>	<p>Can give worthless results if not properly applied</p> <p>A priori knowledge is needed</p> <p>Additional computer time is needed to implement the technique</p>	<p>Most commonly used method. Application in PERT, reliability fault tree analysis, queuing and radiation transport</p> <p>Applicable to almost any problem having criteria indicated.</p>
Russian Roulette and Splitting (RR&S)	Use of probabilities to kill samples in an uninteresting portion of the simulation (RR) and to increase number of samples in regions of interest (S)	<p>Sequential process</p> <p>Events with low probabilities are involved</p> <p>Relative importance of all outcomes is known</p> <p>Useful where importance sampling or expected values are used</p>	<p>Very Limited computation</p> <p>Convenient way to accomplish crude importance sampling</p>	<p>Requires a priori knowledge of importance of intermediate stages</p> <p>May not be effective if used alone</p> <p>Splitting may be difficult to implement</p>	<p>Particle transport, search problems, network analysis, traffic flow and random walk.</p> <p>Usually when low probability events or unimportant events are involved.</p>

CHARACTERISTICS OF VARIANCE REDUCTION TECHNIQUES (Continued)					
VRT	DESCRIPTION OF TECHNIQUE	CRITERIA OF APPLICATION	ADVANTAGES	DISADVANTAGES	TYPICAL APPLICATIONS
Systematic Sampling	Selected random numbers are systematically distributed over the sample space	Random variables are to be generated at the beginning of the problem (Source or Initial Conditions) Relative importance of ranges of sampled variables is unknown	Easy to implement Little additional computation No risk in application Always gives variance reduction	Often gives marginal improvement Effective only in limited number of situations	Could be useful in any problem where random inputs are of interest Examples are in queuing and reliability
Stratified Sampling	Sample space is divided into sections. Sampling is accomplished from each section. More important areas are emphasized	Random variables are to be generated at the beginning of the problem Certain ranges of the variables are more important than the other	Easy to implement Can give great improvement Gives better results than systematic if properly applied Can be optimally applied	Requires a priori knowledge of importance Can lead to worse results if not properly applied Sometimes difficult to define sampling ranges	Queuing Any problem with random conditions such as reliability and network analysis

CHARACTERISTICS OF VARIANCE REDUCTION TECHNIQUES (Continued)					
VRT	DESCRIPTION OF TECHNIQUE	CRITERIA OF APPLICATION	ADVANTAGES	DISADVANTAGES	TYPICAL APPLICATIONS
Expected Value	Include known expected values in the process to replace a stochastic portion of a simulation	Analytical results, probabilities, or expected values of the problem are known Higher moments of the above mentioned portions are not essential to overall simulation	Almost always gives improvement Easy to implement	May require prohibitive analysis or computation	PERT, Radiation transport Limited in other areas Could be used where known results are available for parts of the problem
Statistical Estimation	Include known expected values or probabilities in estimated and not in simulation model	Analytical results, probabilities or expected values of portions of the problem are known Stochastic nature is essential to overall simulation Process is sequential in nature Probability of final outcome is known but small at all intermediate stages	Always gives improvement Can get great improvement Could be the only way to get an answer	May require prohibitive analysis or computation	Primary application in radiation transport Potential to use at any simulation

CHARACTERISTICS OF VARIANCE REDUCTION TECHNIQUES (Continued)					
VRT	DESCRIPTION OF TECHNIQUE	CRITERIA OF APPLICATION	ADVANTAGES	DISADVANTAGES	TYPICAL APPLICATIONS
Correlated Sampling	Some of random numbers are used in successive trials to provide correlation among the outcome in successive trials	Sensitivities studies are of interest Effect of parameter variations to be determined Small effects are of interest	Easy to comprehend Applicable to many situations Little risk when applied Often the only way to detect small effects	May be difficult to implement Sensitive to specific applications	Can be used in any problem where sensitivities are of interest Examples are network design, tactics evaluation, reliability and queuing
History Reanalysis	Takes results of one simulation and reinterprets as results of second simulation weighting answers to remove bias	Results of two or more similar problems are needed Difference in problems may be written as difference in probability distributions	Results are highly correlated thus reducing variance in difference Save computation time for second simulation	Problems may differ in aspects more than probability distribution Variance in the second problem may be prohibitively high in history reanalysis	Potentially many applications. It was used in radiation transport

CHARACTERISTICS OF VARIANCE REDUCTION TECHNIQUES (Continued)					
VRT	DESCRIPTION OF TECHNIQUE	CRITERIA OF APPLICATION	ADVANTAGES	DISADVANTAGES	TYPICAL APPLICATIONS
Control Variates	Using simplified or approximate positively correlated representation for undetermined parts of simulation	Portions of the problem can be approximated with an analytical representation A simple low variance approximation is known	Requires simple calculation Provides considerable flexibility Can give great improvement	Requires understanding of the process Simple analytical approximation may not exist	Potentially can be used at any area where approximate representation of the random variable under estimation is known Has been applied in queuing problems
Antithetic Variates	Using simplified or approximate negatively correlated representation for undetermined parts of the problem	Analytical or approximate representation are known and negatively correlated with the problem variables	Requires simple calculation Provides considerable flexibility Can give great improvement	Requires understanding of the process Costs more than control variates	Could be used in reliability, queuing, sensitivity analysis Has been applied to queuing problems

CHARACTERISTICS OF VARIANCE REDUCTION TECHNIQUES (Continued)					
VRT	DESCRIPTION OF TECHNIQUE	CRITERIA OF APPLICATION	ADVANTAGES	DISADVANTAGES	TYPICAL APPLICATIONS
Regression	Used with linear combinations of parameter being estimated in a simulation model. An approximate minimum variance estimate is included exploiting the inherent correlation among the parameters	Estimated parameters are linear combinations of random variables Correlation among variables is known to exist	Little or no bias results Exploits correlation Little loss if there is no correlation Requires little information about the problem	Increased computation Limited to linear combination of the random variables in its usual form	Almost any problem where the outcome is a linear combination of statistical estimators (Reliability, queuing)
Sequential Sampling	Developing of estimate for parameter to be used in other VRTs by using information generated from previous sampling	Little or no information is available about the process Other variance reduction techniques are to be implemented	Can be almost always applied Requires little or no prior information Can be used in conjunction with other techniques	May require considerable calculations Efficiency may be very low May not be useful in certain problems (with low probabilities) Not well developed	Evaluation of multiple integrals, estimation of distribution parameters and could be used in lifetime studies

CHARACTERISTICS OF VARIANCE REDUCTION TECHNIQUES (Continued)					
VRT	DESCRIPTION OF TECHNIQUE	CRITERIA OF APPLICATION	ADVANTAGES	DISADVANTAGES	TYPICAL APPLICATIONS
Orthogonal Functions	The orthogonal characteristics of certain orthonormal functions are used to formulate a sampling scheme with reduced variance	Multidimensional variables in the problem Multiple integral formulations can be determined	Great possibilities for problems with multidimensional integral	Not well developed for general applications Difficult to implement efficiently Requires considerable calculations Involves sampling from joint random variables	Multiple integrals Applied in nuclear physics Applied when multiple integrals are possible in complex systems
Adjoint Method	The problem is simulated in a backward or reverse sense (mathematical adjoint formulation)	Reverse process can be formulated Starting positions for final outcomes can be defined Mathematical adjoint formulation is known	Can give indication of what importance sampling is required Very powerful when it can be applied Useful when studying system input sensitivity	Not well developed for all applications Difficult to implement Adjoint concept is difficult to formulate for most problems	Radiation transport Could be used in queuing, inventory, etc. If prom can be formulated as integral or differential equations

CHARACTERISTICS OF VARIANCE REDUCTION TECHNIQUES (Continued)					
VRT	DESCRIPTION OF TECHNIQUE	CRITERIA OF APPLICATION	ADVANTAGES	DISADVANTAGES	TYPICAL APPLICATIONS
Transformation	Use a transform of the process being simulated to give a problem with reduced variance when simulated	Approximations are known for parts of the problem An analytical formulation is known Transformed equation can be easily simulated	Permits parametric representation of knowledge about the system Can lead to substantial improvements	Not well developed for most applications May require complete analytical statement of the problem Appears to be limited in scope of application	Used in radiation transport problems Can be used in queuing, inventory, etc.
Conditional Monte Carlo	Imbeds problem in a larger process using conditional probabilities in larger process	Process is complicated, but can be embedded in a simpler simulation	When applicable, can give great improvement Some algorithms are available for network application	Sometimes difficult to recognize applicability	Stochastic PERT, CPM, and inventory

Appendix I: SQUADRON.DAT File Example (33)

Squadrons (squadron.dat)

SQUADRONS.305

NUMBER.OF.MISSION.CLASSES: 12
(N.MISSION.CLASS)

AIR.SUPERIORITY
DEEP.STRIKE
GROUND.SUPPORT
JAMMER
MULTI.ROLE
RECCE
WEASEL
AWACS
JSTARS
TANKER
TBM
BPI

(Mission class names (MC.NAME))

NUMBER.OF.SORTIE.PROFILES: 14
(N.SORTIE.RATE.PROFILE)

1001 "A-10"

(Sortie rate profile ID (SRP.ID) and Name (SRP.NAME))

DAY.IN.THEATER..AUTH.QTY.SORT/DAY..AC.MAX.SORT/DAY
1.00 4.00 4.00

(Start time from arrival in theater (SRE.START.TIME), Nominal sortie rate (SRE.MAX.RATE), Maximum sortie rate (SRE.MAX.RATE))

END.PROFILE

1002 "F-16"

DAY.IN.THEATER..AUTH.QTY.SORT/DAY..AC.MAX.SORT/DAY
1.00 3.60 6.00
6.00 2.50 5.00

END.PROFILE

...

NUMBER.OF.SQUADRONS: 30

(Number of squadrons (will be added to N.TBM.UNIT to form N.SQUADRON))

1001 "1ST FTR"

(Squadron ID (SQN.ID) and Name (SQN.NAME))

SIDE..SUP.CMD.ID..TYPE.AC.ID..AUTH.QTY..AR.PRIORITY...RECCE.PRIORITY
1 1102 1005 24 0 0

(Side the squadron belongs to (1=BLUE, 2=RED) (SQN.SIDE), Superior command ID (SQN.COMMAND), Aircraft type ID (SQN.TYPE.AC), Quantity of aircraft (SQN.QTY.AC), Priority for air refueling (must be at least 0 and at most 100) (SQN.REFUEL.PRIORITY), Squadron reconnaissance priority (SQN.RECCE.PRIORITY))

MOB.ID..DISP.AB.ID..SERV.KIT.ID..SORT.PROF.ID..MISSION.CLASS
1002 1005 1005 1005 AIR.SUPERIORITY

(Main operating base ID number (SQN.MOB), Dispersal base ID number (SQN.DISPERSAL.BASE), Service Kit ID number (SQN.SERVICE.CONFIG), Sortie profile ID number (SQN.SORTIE.RATE.PROFILE), Squadron mission class (SQN.MISSION.CLASS))

```

..DCA..ODCA..HVAA..BARC..FSWP..EAIR...STI...CAS...BAI...INT...OCA..OTBM..DTBM
100 100 100 100 100 100 0 0 0 0 0 0 0 0
.DSED..SSUP..CSUP..ESUP..SJAM..CJAM..EJAM..RECC..SREC...AEW...AAR..LIFT..XXXX..RESV
0 0 0 0 0 0 0 0 0 0 0 0 0 100

```

(Assigned squadron effectiveness for each type mission (percent)
(MSQ.ASSIGNED.EFFECTIVENESS))'

ORDERS

1.2 FOB 1005 0.25 UNIF 1.0 1.5

1.2 SORTIE.PROFILE 1007

END.ORDERS

1002 "1ST FTR-BMBR"

```

SIDE..SUP.CMD.ID..TYPE.AC.ID..AUTH.QTY..AR.PRIORITY...RECCE.PRIORITY
1 1102 1002 24 0 0

```

```

MOB.ID..DISP.AB.ID..SERV.KIT.ID..SORT.PROF.ID..MISSION.CLASS
1002 1005 1002 1002 DEEP.STRIKE

```

```

..DCA..ODCA..HVAA..BARC..FSWP..EAIR...STI...CAS...BAI...INT...OCA..OTBM..DTBM
100 100 100 100 100 100 20 100 100 100 100 100 100

```

```

.DSED..SSUP..CSUP..ESUP..SJAM..CJAM..EJAM..RECC..SREC...AEW...AAR..LIFT..XXXX..RESV
0 0 0 0 0 0 0 100 0 0 0 0 0 100

```

ORDERS

1.2 MSN.CLASS MULTI.ROLE 2

END.ORDERS

...

END.SQUADRONS

Notes

1. The squadron mission effectiveness is multiplied by the type aircraft mission effectiveness to form the mission effectiveness used in the LP that allocates sorties to missions.
2. Squadron Orders Format

Time Order <Arg1><Arg2> where Time = Time to execute order

Order	Arguments	Effect
DOB	<air base ID>	change dispersal base
MOB	<air base ID>	change main operating base
FOB	<air base ID><prob return to MOB> <return to MOB delay time function>	change squadron operations to a forward operating base
SORTIE.PROFILE	<sortie profile ID>	change sortie profiles
MSN.EFF	<mission><effectiveness>	change squadron mission effectiveness
SUPERIOR	<air planning command ID>	change superior command of the squadron
MERGE	<squadron ID>	merge with another squadron of the same type AC
AC.QTY	<change in aircraft quantity>	add/subtract aircraft inventory
MSN.QTY	<mission class>	change mission class
ARRIVE		arrive in theater
KIT.ARRIVE	<kit.ID>	provides squadron with this type of service kit
AR.PRIORITY	<0-100>	changes in air refueling priority

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Vita

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After spending three years working in the civilian sector, 1Lt Bednar attended Officer Training School in Maxwell AFB, Alabama in 2001. His first assignment was working as an Assignments Analysis Officer for Headquarters Air Combat Commands Department of Personnel. In 2003, he was selected to attend the Air Force Institute of Technology's Graduate of Operations Research program. After his completion of the program, 1Lt Bednar will be assigned to the Air Force Research Labs Information Directorate, Advanced Computing Technology branch in Rome, NY.

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14. ABSTRACT As an Air Force Chief of Staff endorsed topic, Air Force Studies and Analyses Agency (AFSAA) requested an effective and efficient way to reduce the variance in analysis results from THUNDER. THUNDER is a large-scale discrete event simulation of campaign-level military operations and is used to examine issues involving the utility and effectiveness of air and space power in a theater-level, joint warfare context. Given the large number of stochastic components within THUNDER, results are produced with highly variable measures of effectiveness (MOEs), causing difficulties in evaluating alternative force structures, weapon systems, etc. This work responds to AFSAA's request by examining the application of Common Random Numbers (CRN), Antithetic Variates (AV), Control Variates (CV), and a combination of AVs and CVs and a combination of CRNs and CVs. The difference between the normal and variance reduction technique halfwidths for 95% confidence intervals were examined. Analysis of the correlation between MOEs and the random inputs in the CV technique gave insight into the workings of THUNDER. A new, state of the art combined multiple recursive generator was incorporated into THUNDER to synchronize the random inputs for CRN and AV. The result is methodology for implementing all four variance reduction techniques.					
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