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Comparisons of Ballistic Trajectory Simulations Using Artillery Meteorological Messages Derived from Local Balloon Data and Battlescale Forecast Model Data for the 1998 SADARM IOT&E Firings

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13. ABSTRACT (Maximum 200 words)

This report describes meteorological (Met) analyses of data collected during the Sense and Destroy Armor (SADARM) Initial Operational Test & Evaluation (IOT&E) firings that occurred during the summer of 1998 at Fort Greeley, Alaska. Due to the complex terrain and local wind conditions encountered in the test area during the IOT&E, the Met study was proposed as a way to evaluate current and future artillery Met forecasting capabilities to improve SADARM targeting accuracy. This report includes Ballistic trajectory simulation analyses using raw and forecast Met values and corresponding actual impact data from the IOT&E firings.

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Preface

The research presented in this report was partially funded by the Office of the Project Manager, Artillery Munitions Systems (OPM-ARMS). The U.S. Army Research Laboratory was tasked to perform meteorological (Met) analyses of data collected during the Sense and Destroy Armor (SADARM) Initial Operational Test & Evaluation (IOT&E) firings that occurred during the summer of 1998 at Fort Greeley, Alaska. Due to the complex terrain and local wind conditions encountered in the test area during the IOT&E, the Met study was proposed as a way to evaluate current and future artillery Met forecasting capabilities to improve SADARM targeting accuracy. This report describes results of ballistic trajectory simulation analyses using raw and forecast Met and corresponding actual impact data from the IOT&E firings.

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Executive Summary

Data from the Sense and Destroy Armor (SADARM) Initial Operational Test & Evaluation (IOT&E) firings at Ft. Greeley, Alaska during the summer of 1998 provided the opportunity to compare trajectory simulations using current Rawinsonde (radio wind sounding) balloon Observations (RAOB)-based meteorological (Met) messages to the future capability of using forecast model-based messages. The goal of the study was to determine if Met model-derived data could add value to the firing calculations, being more representative of the entire trajectory of SADARM shells than data supplied only by a gun-area RAOB. The research presented in this report was partially funded by the Office of the Project Manager, Artillery Munitions Systems (OPM-ARMS).

Actual submunition impact data were compared against predicted impacts derived from a trajectory simulation program (General Trajectory Model-Version 3 [GTRAJ3]) that relies heavily on Met data for determining trajectories. Two types of Met data were input to GTRAJ3 (RAOBs and data generated by the Battlescale Forecast Model [BFM]), in order to test which type most accurately represented the "true" atmosphere.

The SADARM IOT&E firings occurred over a short range of slightly less than 20 km, with current RAOB data (less than 2 h old) and relatively low wind speeds from the surface to the peak of the trajectories. Under such conditions there is typically little advantage to be gained by using forecast model data. Also, complex factors such as varying surface albedo and very rugged terrain had an adverse effect on the accuracy of the BFM. Consequently, Met messages derived from RAOB's were somewhat more accurate than those derived from the model. Still, in most cases the BFM performed reasonably well in representing the "true" atmosphere. Follow-up studies are underway using data collected during SADARM test missions at Yuma Proving Ground, AZ during the first half of 2000. The results indicate that the BFM is capable of significant accuracy improvements over RAOBs under more nominal operating conditions. A technical report summarizing these findings is forthcoming.

1. Introduction

1.1 Purpose and Overview

The purpose of this study was to evaluate the suitability of mesoscale meteorological (Met) model output for artillery aiming applications. Current battlefield doctrine involves the use of Rawinsonde (radio wind sounding) balloon Observations (RAOBs) to obtain the necessary Met information for generating artillery Met messages. The U.S. Army Research Laboratory (ARL), Battlefield Environment Division's Battlescale Forecast Model (BFM) was used to generate forecast Met data and artillery Computer Met Messages (CMMs) for comparison against those data obtained from RAOBs.

During July and August 1998, the Initial Operational Test & Evaluation (IOT&E) for the Sense and Destroy Armor (SADARM) system was conducted at Ft. Greely, Alaska. The Office of the Project Manager, Artillery Munitions Systems (OPM-ARMS) managed the test program. Data from four mission-days were analyzed for this study, with 24 rounds fired each mission-day. The SADARM round contains two submunitions; therefore, approximately 192 submunition-recorded impacts were analyzed. The OPM-ARMS partially funded the research presented in this report**.**

Although it is valid to directly compare BFM output to RAOB data, the ultimate goal of employing models such as the BFM is to enhance the accuracy and applicability of the Met data provided by a RAOB (or other measurement source such as a wind profiler) across the *entire* artillery gun-target region. It is of great interest to compare the accuracy of artillery fire that uses RAOB-based CMMs to the accuracy for which a Met model (in this case the BFM) supplied similar messages. This was the approach utilized in this study. (A direct comparison of CMMs is shown in section 6.1.) The SADARM firings were simulated using the Armament Research Development and Engineering Center (ARDEC), Firing Tables Branch's General Trajectory Model-Version 3 (GTRAJ3). The GTRAJ3 simulations were run using only RAOB-based CMMs, then again using only BFM-based CMMs. The simulated impact points from each GTRAJ3 run were compared to actual submunition impact coordinates from the IOT&E data set. In this way, the Met data most representative of the true atmosphere could be determined based on which simulation placed its impact point closest to the actual impact coordinates.

1.2 Background

As for all effective artillery firings, SADARM firings include Met aiming adjustments to compensate for the variations of atmospheric wind, temperature, and density along the shell's trajectory. A study of the targeting errors for the ER-155* firing the M549A1 concluded that for an extended range of 28.1 km, 42 percent of the range error (that is, along the initial firing axis) and 56 percent of the deflection error (that is, perpendicular to the initial firing axis) is attributable to atmospheric variations. Most of the remaining firing errors are due to muzzle velocity inaccuracies, with minor contributions due to aimimg and location errors, and the rocket used to assist the projectile. It was further concluded that approximately half of the targeting accuracy error that occurs during unassisted cannon firings can be attributed to Met effects. [1] Thus, reducing the Met errors in the data used for the firing calculations can significantly improve the accuracy of the cannon firings that launch the SADARM submunitions into the target areas.

In addition to Met influences on its overall trajectory, the SADARM is especially sensitive to Met variables as the submunition is deployed, slows, and descends over the target area. Unanticipated low-level wind speed and directional shears and/or turbulence can adversely impact the descending submunition by displacing it further from the targets. Other concerns focus on accurate target area prediction of clouds, precipitation, icing, and visibility, all of which can adversely impact the effectiveness of the weapon system. [2] In rapidly changing weather conditions over space and time, 1- to 2-hour old RAOB data from a balloon launched at the gun location may not accurately depict conditions along the trajectory, at the peak of the trajectory (the apogee point), or over the target area. This becomes more likely as extended ranges of SADARM firings will approach 40 km and beyond, and future Army doctrine calls for unguided cannon firings with ranges in excess of 100 km. Current capability using gun-vicinity RAOBs will not accurately depict trajectory or target area Met at these extended ranges. The ARL's BFM is the first attempt to predict conditions in 4-D (four dimensional) (three dimensions in space, plus time) across the artillery battlefield. The model is used to answer the Met data time-staleness problem, the spatial variability issues of extended range firings, as well as the terrain complexity problems from gun-to-target that SADARM (and other artillery weapon systems) will face.

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*The ER-155 (Extended Range-155 mm diameter) is a rocket-assisted round. Although the SADARM rounds evaluated/simulated in this study were unassisted 155 mm rounds, the effects of atmospheric conditions were assumed to be similar in magnitude. [1]

2. The SADARM Weapon System

The SADARM is a submunition delivered by a 155 mm artillery round. In its current configuration, it is fired over a range of about 20 km with an apogee of just under 5 km above ground level (AGL). Somewhere between 1500 and 1000 m AGL on the downward leg, the artillery round ejects two submunition canisters. Each canister deploys a Ram-Air Inflated Decelerator (RAID) parachute. At around 500 m AGL a second chute is deployed (called the Vortex Ring Parachute or VRP). The VRP causes the descending canister to spin in a conical search pattern. Millimeter-wave and infrared sensors search for armored vehicle targets during the VRP descent phase, beginning at 130 m AGL. The maximum radius of the search pattern is 75 m. When a target is sensed, an Explosively Formed Penetrator (EFP) firings from the canister.

Some of the characteristics of the EFP performance (against the actual targets) are classified; consequently no EFP operational results will be discussed herein. All references to "impacts" in this study are concerning RAID ground impacts. From a ballistics standpoint, the RAID reacts to the atmospheric conditions within the final 1000 m AGL in an almost identical fashion to the submunition canister descending on the VRP. Consequently, the RAID impact points (which are precisely surveyed) may be assumed to represent the impact of the SADARM submunition canisters. Each round produces two RAID impacts, one from the "forward" and the other from the "aft" submuntion canisters.

3. The Battlescale Forecast Model

The BFM consists of three modules:

- preprocessing,
- the actual predictive model, and
- post-processing.

The preprocessing or "initialization" module consists of input file handling routines and a 3-D (three dimensional) objective (3DOBJ) analysis routine that captures all recent local and large-scale Met data available at the forecast time and produces the initial fields that are required to start the forecast module. The 3DOBJ routine also provides time-dependent lateral boundary values during the model run. Initialization data used for the SADARM IOT&E cases consisted of large-scale forecast fields from the Navy Operational Global Atmospheric Prediction System (NOGAPS) 1° horizontal grids. (Such fields are required for any fine-scale model to help account for larger-scale atmospheric changes at the desired forecast hour.) Additional initialization data came from standard regional RAOBs launched twice each day at several locations across Alaska. Most importantly, the last source of initialization data was the actual RAOB launched at the gun location approximately 60 to 120 min prior to each SADARM firing. (The significance of initializing the BFM with a local RAOB will be illustrated in section 6.) All initial data are interpolated to 55 flat levels by the 3DOBJ, and a Barnes-type analysis is performed to produce data at each horizontal grid point. Finally, the flat levels are linearly interpolated in the vertical to the 32 terrain-following levels required by the forecast module. The interpolation to terrain-following levels requires a terrain database. Normally, a worldwide military database called Digital Terrain Elevation Data (DTED) is used by the BFM. However, there were "holes" in DTED in the Ft. Greely, Alaska region, and consequently a U.S. Geological Survey (USGS) database was substituted. Although not as fine-scale as DTED, the USGS database had more than adequate resolution for the BFM application.

The forecast model module that was used as part of the BFM package is Yamada's Higher Order Turbulence Model for Atmospheric Circulations (HOTMAC). This module accepts the 3DOBJ output and conducts the actual predictive process. To produce the true 0-h wind fields in a dynamically adjusted fashion, a 3-h model spin-up integration is performed. During the spin-up, model surface temperatures can also be nudged to recorded surface observations from the model domain area that was valid at the initial model time. The HOTMAC also includes physical parameterizations for turbulent mixing, both long- and short-wave radiative transfer, the surface energy budget, and cloud and precipitation formation. [3,4] During the HOTMAC run, forecast output is produced by solving the atmospheric predictive equations in a hydrostatic formulation along with nudging of parameters towards the larger-scale NOGAPS solutions.

The third BFM module consists of post-processing HOTMAC output in order to produce forecasts of five standard variables:

1. temperature,
2. wind speed,
3. wind direction,
4. moisture, and
5. height or pressure at each level of model output.

For SADARM applications, gun-area[†], apogee, and low-level target area, Met parameter forecasts were produced from this final module. The BFM was run to produce output at 5 km horizontal resolution across a 300 km x 300 km domain centered near the apogee.

In the original BFM software, CMMs were created by linearly interpolating from 4-D grid points surrounding the apogee point itself. However, the BFM software was modified because of two considerations:

1. *The desire to use the surface[‡] wind at the gun.* To address this consideration, a "merged" CMM was produced that uses surface winds (Line 0 in the Met Message) at the gun location. The remaining levels (Line 1 upward to the apogee height - Line 12 in the case of SADARM) are at the apogee point. The advantage of such a merged profile was that Met data that were valid at the firing point for the lowest level were used instead of at the apogee (that was located approximately 10 km away).

[†] The BFM uses "sectors" to represent the gun and target areas. Thus, the precise gun and target locations are not needed for the model to produce a CMM.

[‡] The term "surface" actually refers to 10 m above the surface.

2. *The possibility of the terrain height at the apogee point being higher than that at the gun location.* In this situation, CMM Lines 1, 2, and so forth are also from the gun location. The CMM lines switch to the apogee point only when the terrain at that location is cleared.

A disadvantage of using BFM Met data that are valid at the gun location (for lowest level[s]) is that the atmospheric conditions in the target area are not represented in the GTRAJ3 simulation. However, the BFM produces a second Met message, called a MET-TALL (Meteorology-Target Area Low Level) [§]. The MET-TALL, as its name implies, is a Met message that has been interpolated to the target area. Both the CMM and the MET-TALL were used in each GTRAJ3 simulation in this study, in order to more accurately incorporate Met information at the gun, apogee, and target.

For each of the IOT&E mission-days, the BFM was initialized with a 1-h old gun-area RAOB. The model was then run to produce forecast CMMs that were valid at 1 h into the future. For example, if the firing was scheduled at 2000 UTC (Universal Time Coordinate) [**], a 1900 UTC gun-area RAOB was released for the gun crews to use in aiming the cannons. The BFM was initialized with that same RAOB and a 1-h forecast CMM was generated, valid at 2000 UTC. The impact of this very short forecast period on the performance of the BFM will be discussed in section 7.

[§] The MET-TALL (as used by GTRAJ3) extends from the surface up to 1500 m AGL.

[**] UTC, equal to local Ft. Greely time plus 8 h.

4. The GTRAJ3 Trajectory Simulation Model

The IOT&E series of SADARM artillery firings were simulated using the ARDEC, Firing Tables Branch's GTRAJ3. This model is widely accepted in the artillery community as an accurate simulator of live artillery round trajectories. It utilizes applicable aerodynamic and ballistic factors and allows the operator to input measured muzzle velocity, propellant temperature, gun and target elevation, azimuth/elevation aiming angles and, of course, a CMM and MET-TALL.

The GTRAJ3 uses the point mass equations of motion (EOM) to simulate the trajectory of a projectile in flight through user-defined time steps. It has a variety of integration and output options; however, for this study GTRAJ3 continued its integration from the gun elevation to the target elevation in 1-s time steps. Its coordinate system and output parameters will be described in a section 5.3.

The GTRAJ3 is very similar to the Battery Computer System (BCS) software that is used by the gun crews to determine their aiming angles[††]. Therefore, a GTRAJ3 simulation that incorporated the same CMM as was used by the gun crews in the BCS was considered to be a good indicator of exactly where the live rounds were targeted. This GTRAJ3 capability proved very useful in evaluating the validity of some of the results presented herein, as will be explained in section 5.2. However, it must be clearly noted that any statements made throughout the remainder of this document concerning the proximity of the aiming points to the targets are solely based on *GTRAJ3 simulation results*. Such statements are in no way a reflection on the accuracy of the BCS software or on the quality of the aiming procedures that were employed by the gun crews.

[††] Based on personal communications with SADARM test personnel.

5. Data Analysis Process

5.1 The Analysis Concept

The flight of the SADARM rounds was dictated by the ambient atmospheric conditions along their trajectory. When the GTRAJ3 simulations resulted in impacts that were very close to the actual impacts, it was assumed that the Met data incorporated into the simulations were extremely accurate. The closer the GTRAJ3 simulation came to the actual RAID impacts, the more accurate the Met message was taken to be (i.e., the more closely representative of the "true" atmospheric conditions). (The other types of targeting errors mentioned in Section 4, such as muzzle velocity, gun/target location, etc were included this study because these values were precisely known and were input to the GTRAJ3 simulations.) Thus, GTRAJ3 was run once using a RAOB-based CMM (RCMM) and the specific input conditions for a particular firing (gun azimuth/elevation angles, propellant temperature, measured muzzle velocity, etc.). The trajectory model was then re-run with the identical input parameters but substituting a BFM-derived CMM (BCMM) for the RCMM. The impact coordinates from both simulations were then compared to the actual RAID impact locations.

The RCMMs were derived from balloon data that were taken from launches near the gun locations. These data were assumed to be valid at the apogee point, as is the current doctrine for artillery Met. The BFM-based CMMs and MET-TALLs were derived as described in section 3.

5.2 Data Set Limitations and Specifications

The SADARM IOT&E was conducted during July and August 1998. A set of 4 mission-days was included in this study. (A fifth mission, Mission 4 on 21 August, was excluded since the target area was affected by strong localized winds from a thunderstorm "microburst." These data are included in the appendix.) Neither the gun-area RAOB nor the BFM was capable of detecting this feature, making impact comparisons meaningless. Most of the rounds missed the target area by a substantial margin, some to the extent that their precise impact points were never surveyed. On any given day, each of the five to eight guns fired multiple rounds. Twenty-four rounds were fired during each mission, resulting in approximately 48 RAID impacts. Due to the rapid-fire volleys and certain range instrumentation limitations, not every RAID impact was accounted for. The actual number of accountable impacts varied from 42 to 46 during the four missions. The mission summary is listed in table 1.

Table 1. SADARM IOT&E mission summary

Mission number	**Date**	**Time (UTC)**	**Number of guns**	**No. of impacts**
1	28 Jul	2250	6	46
2	4 Aug	2200	7	46
3	11 Aug	2030	8	42
5	24 Aug	0250	5	45

The participating guns fired a volley of three or more rounds during each mission. The rounds in each volley were aimed in precisely the same way; however, slight differences in the weight of the rounds and the varying gun tube effects (primarily as the tube heated during the rapid-fire volleys) resulted in a scattering of RAID impacts.

The IOT&E data set was provided by analysts at the OPM-ARM. Included were applicable data such as gun ID numbers, locations and elevations, firing times, RAID carrier serial numbers, aiming angles, muzzle velocities, propellant temperatures, and target and RAID impact coordinates. All locations were given in Universal Transverse Mercator (UTM) coordinates (X/Y values in meters from the reference point). The firings were directed from the NNE[‡‡] to the SSW over a range of about 20 km (figure 1).

The elevation at the guns was approximately 380 m above mean sea level (MSL). They were typically grouped in two tight clusters, separated by about 1 km, as depicted in figure 2. This gun positioning was for Mission 3, during which the most guns participated. The other mission-days had almost identical positioning although fewer guns were involved.

[‡‡] The 16-point compass directions are similarly abbreviated throughout this document.

Figure 1. SADARM IOT&E gun/target positioning.

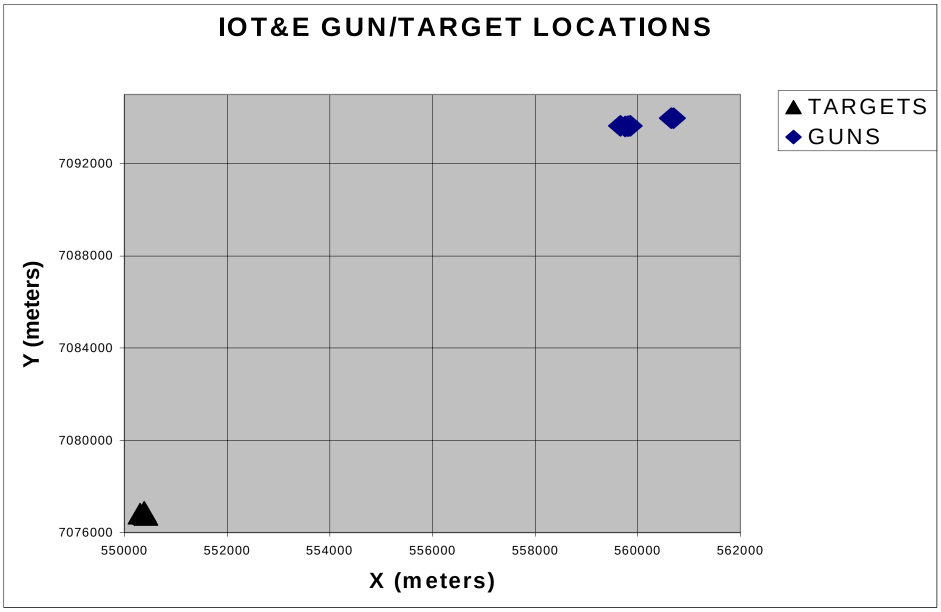
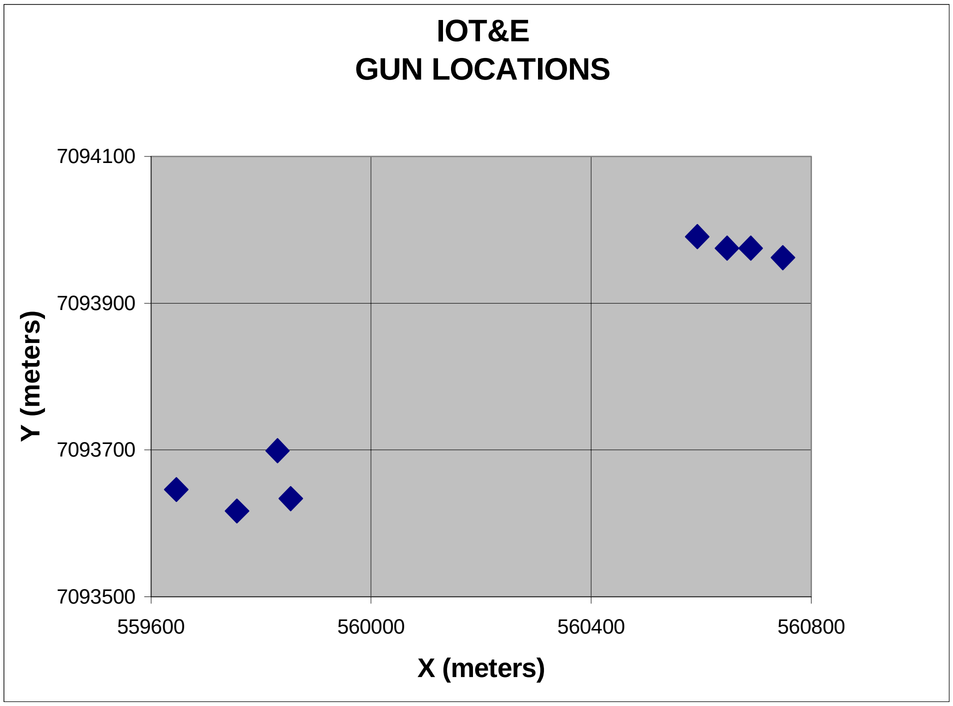
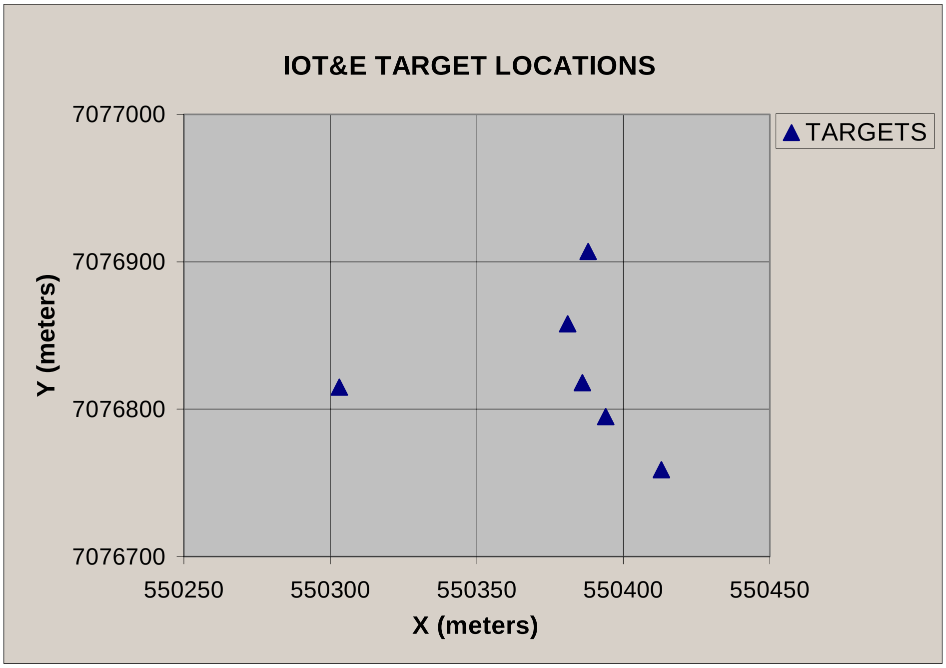


Figure 2. SADARM IOT&E gun locations for Mission 3.



The six targets were situated approximately 20 km from the guns and at an elevation of 460 m MSL. They were grouped relatively close together and roughly in a line (with one exception) as depicted in figure 3.

Figure 3. SADARM IOT&E target locations.



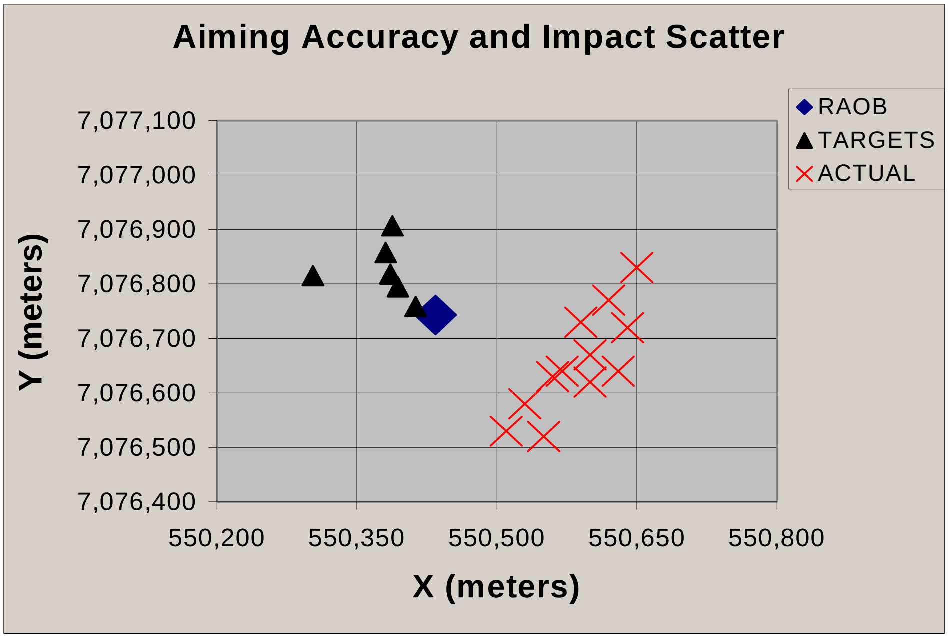
An East-West oriented mountain range lies a short distance to the south of the target area, divided by a deep North-South canyon. The canyon is oriented almost along the trajectory path. These abrupt terrain features just to the south of the firing range can have a pronounced effect on the target area winds due to a funneling effect, a fact that was quite evident during some of the missions.

The initial analysis approach (which was rather qualitative) was to create plots showing target locations, simulated GTRAJ3 impact points, and the forward and aft RAID impact coordinates. For some of the missions it was fairly evident which simulated impact (using BCMMs or RCMMs) came closest to the actual RAID impacts. For others it was impossible to tell, and so a method using mean radial miss distance (MRMD) calculations was implemented to quantify the results (explained in section 5.4).

Variability in the aiming of the guns (as indicated by the GTRAJ3 simulation) created a minor difficulty in the analysis. Although the primary focus of this study was to compare simulated impacts to actual impacts, some reference to the targets was also necessary. Those firings that were aimed to hit farther from the targets were not considered to be completely valid data points for the comparisons. This was because the

GTRAJ3 simulations would have come out somewhat differently had the guns been aimed differently. Figure 4 illustrates these concepts.

Figure 4. Aiming accuracy and impact scatter.



The scattering of the "x's" depicts the typical spread of RAID impacts (labeled "ACTUAL"). The diamond symbol (labeled "RAOB") indicates where GTRAJ3 calculated the impact would occur, based upon that gun's aiming angles and using the RCMM as input by the firing crew. This gun was aimed within specifications (within 75 m of two of the targets); for many of the firings, however, this was not the case. For firings where the gun was aimed farther from the targets (based on the GTRAJ3 simulation using the RCMM), it was more difficult to draw any firm conclusions.

5.3 Coordinate Transformations

GTRAJ3 utilizes a coordinate system relative to the gun, where "E1" is the distance along the axis of the aiming angle and "E3" is the distance perpendicular to that axis. The IOT&E data set contains UTM coordinates, where "Y" is the distance from the origin (the international date line at the equator) relative to True North (TN) and "X" is the distance from the origin relative to True East (TE). In this study, the (E1/E3) coordinates of the simulated impacts had to be converted to their UTM equivalents. The trigonometric calculations are described below and illustrated in figure 5.

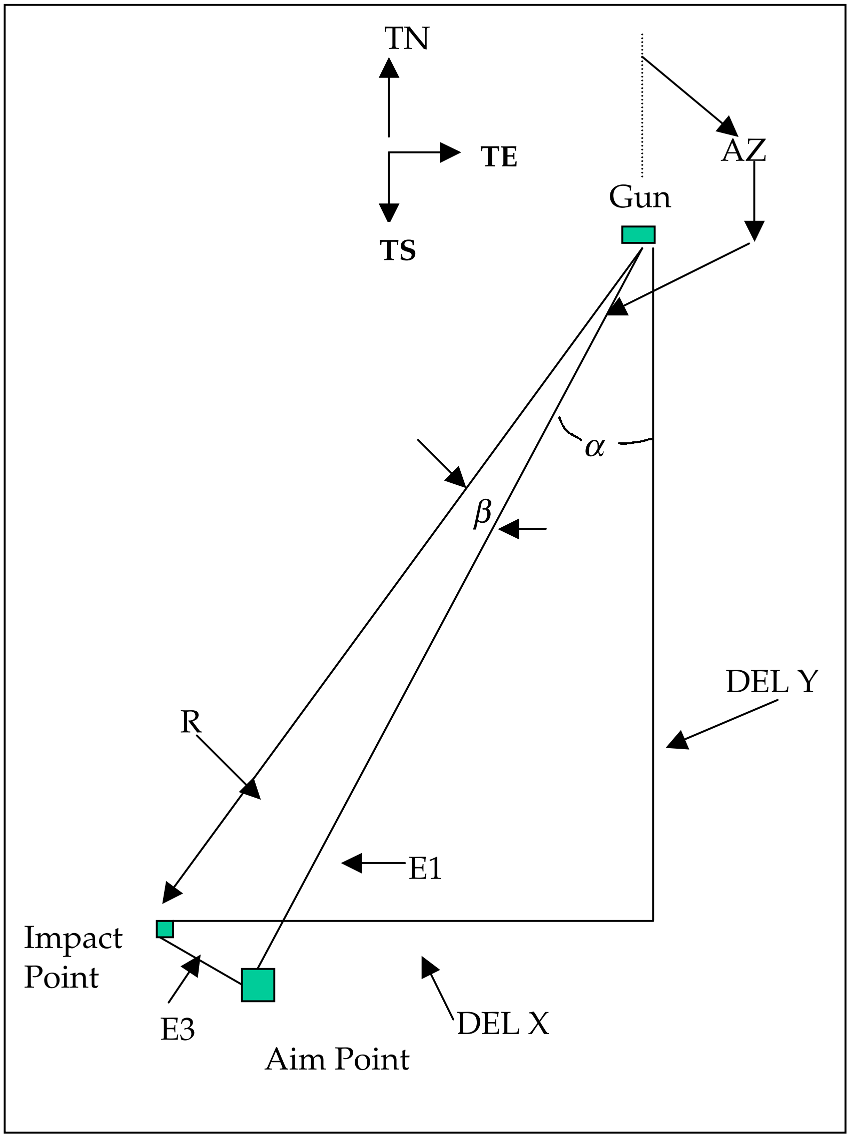


Figure 5. Conversion from GTRAJ3 "E" coordinates to UTM.

In equations (1) to (5),

IP stands for "Impact Point,"
AZ is the firing azimuth angle, measured from TN, given in mils,
R is the range, gun-to-impact.
The angle "α"is the measure from (True South) TS to the E1 line.

Converting from AZ (mils) to α (degrees) is:

$$\alpha = \left(\frac{360AZ}{6400} \right) - 180 \tag{1}$$

The angle "β" is the angular change from the firing azimuth to the impact point:

$$\beta = TAN^{-1}\left(\frac{E3}{E1} \right) \tag{2}$$

The impact range "*R*" is simply:

$$R = \sqrt{E1^2 + E3^2} \tag{3}$$

The "DEL X" and "DEL Y" values are:

$$\Delta X = (R)\sin(\alpha + \beta)$$

$$\Delta Y = (R)\cos(\alpha + \beta) \tag{4}$$

The "X" and "Y" UTM coordinates of the impact are then:

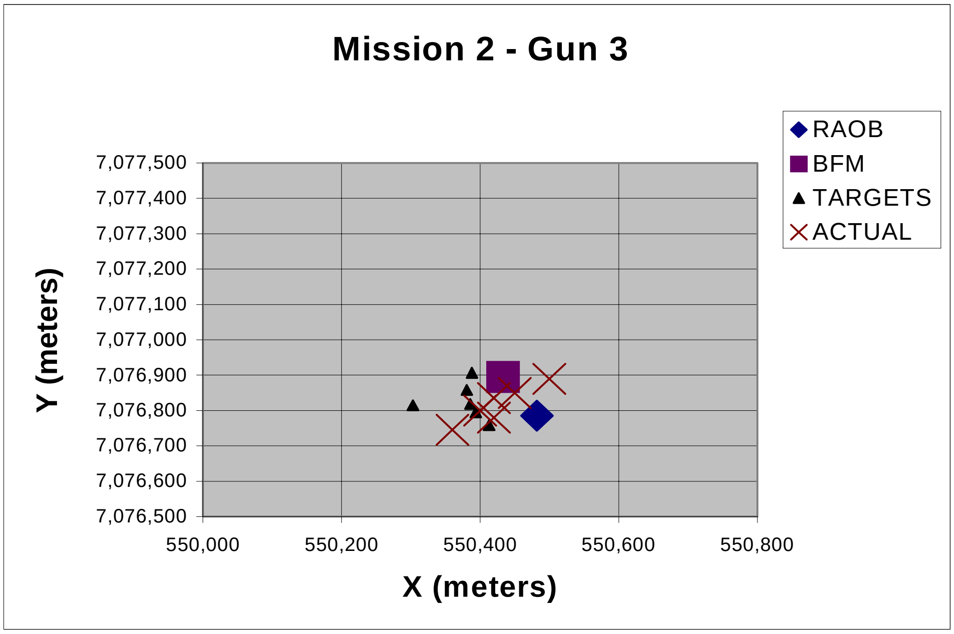
$$X_{IP} = X_{GUN} - \Delta X$$

$$Y_{IP} = Y_{GUN} - \Delta Y \tag{5}$$

5.4 MRMD

To begin the analysis, X/Y plots of each firing were prepared showing the actual RAID impact points. The plots also included target locations and the locations of the GTRAJ3 simulated impacts. For some of the plots, it was relatively easy to see which GTRAJ3 simulation (BFM-based or RAOB-based CMM) came closest to the actual RAID impacts. For other missions, however, this type of subjective conclusion was not readily evident. Figure 6 illustrates this point.

Figure 6. MRMD illustration.



The GTRAJ3 simulated impacts are close together, the one using the BCMM falling about 100 m to the northwest of that using the RCMM. The two simulations were run with identical aiming angles, propellant temperature, and muzzle velocity from Mission 2-Gun 3. This gun fired a volley of three rounds during the mission. With each round containing two RAIDs, a total of six actual impacts resulted.

When viewing figure 6 it is difficult to tell for certain which simulated impact point lies closest to six actual impacts. Using a simple Pythagorean theorem calculation, the distance (called the Radial Miss Distance [RMD]) from both simulated impact points to each of the actual impact points was determined.

$$(RMD)_i = \left(\sqrt{(X_A - X_B)^2 + (Y_A - Y_B)^2}\right)_i \tag{6}$$

In equation 6, the subscript "A" refers to the "Actual" impact coordinate and "B" refers to the simulated point using the BCMM, for the "ith" pair of actual and simulated impact coordinates. The average of the "n" RMDs (in this case n=6), termed the MRMD, was then calculated.

$$(MRMD)_B = \frac{\sum_{i=1}^{n} RMD_i}{n} \tag{7}$$

The MRMD value was also found for the GTRAJ3 RCMM simulation. The MRMD values for BFM and RAOB simulations were then directly compared, as a quantitative indication of which CMM produced the best results (that is, closest to the actual trajectories of the SADARM rounds). The plots and the MRMD comparisons will be discussed in section 6.

In the case of figure 6, the MRMD values were almost identical, 89 m for RAOB-to-actual and 94 m BFM-to-actual.

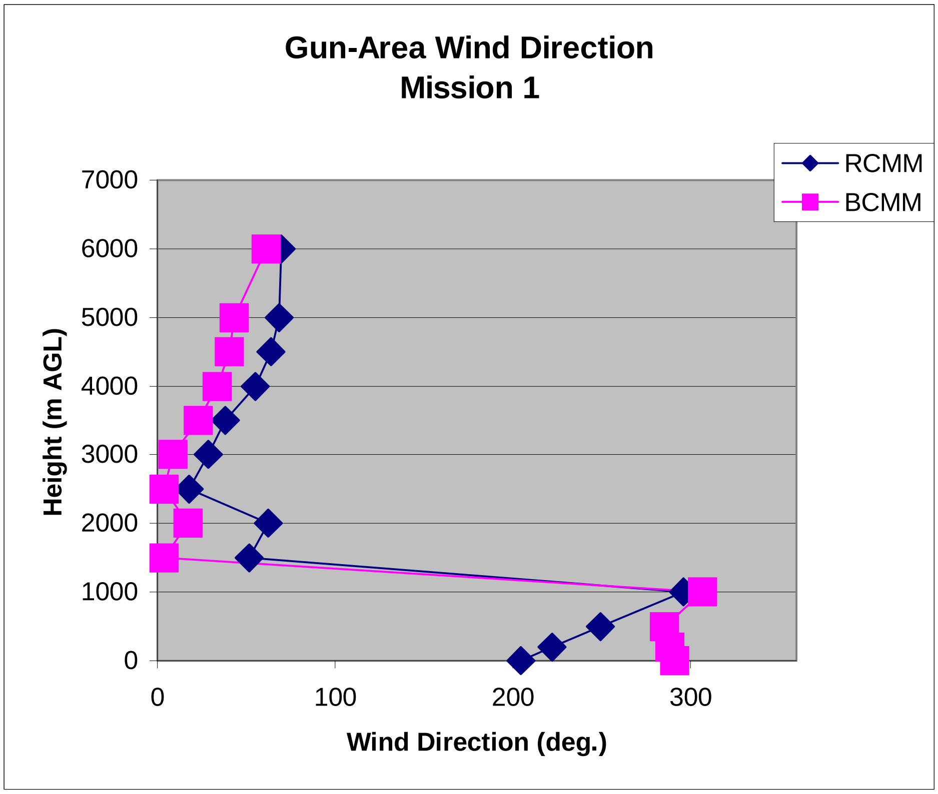
6. Test Results

Section 6.1 discusses direct comparisons between a RCMM and the corresponding BCMM. The subsequent sections describe the scatter plot and GTRAJ3 simulation results for Missions 1 to 3 and 5. The Mission 4 results were not considered a part of the main study but were included in the appendix. Throughout these sections the term "RAOB" means the GTRAJ3 simulation that incorporated a RCMM. Likewise, "BFM" is the simulation that incorporated a BCMM.

6.1 A Direct RAOB-based and BFM-based Met Message Comparison

Figure 7 depicts a side-by-side comparison of wind directions in a RCMM and a BCMM. It is shown here as a graphical example of directly comparing RAOB- and BFM-produced data.

Figure 7. Mission 1 gun area CMM comparisons.



Clearly most of the heights are different. A wind direction plot was selected since it was for this parameter that the greatest differences were noted between RCMMs and BCMMs in the four missions. Much smaller differences were observed with the other three Met parameters (wind speed, temperature, and pressure).

Table 2 summarizes the root mean square error (RMSE) values for the four parameters and the four mission-days. RMSE was calculated as follows:

$$RMSE = \sqrt{\frac{1}{k}\sum_{i=1}^{k}\left(B_i - R_i\right)^2} \tag{8}$$

where,

"B_i" = the BCMM value at the ith height,
"R_i" = the RCMM value at the ith height, and
"k" = the number of levels in the CMM.

Thus, the smaller the RMSE value, the smaller the overall difference between BCMM and RCMM.

Table 2. Summary of RMSE values for the IOT&E Met parameters

		RMSE value		
Mission no.	**Temp. (° K)**	**Pressure (hPa)**	**WD (deg)**	**WS (kts)**
1	2.8	0.9	39.4	0.8
2	1.2	0.7	31.1	2.0
3	1.6	1.1	45.8	2.0
5	1.5	1.0	43.9	2.8

NOTE:

WD	wind direction
WS	wind speed

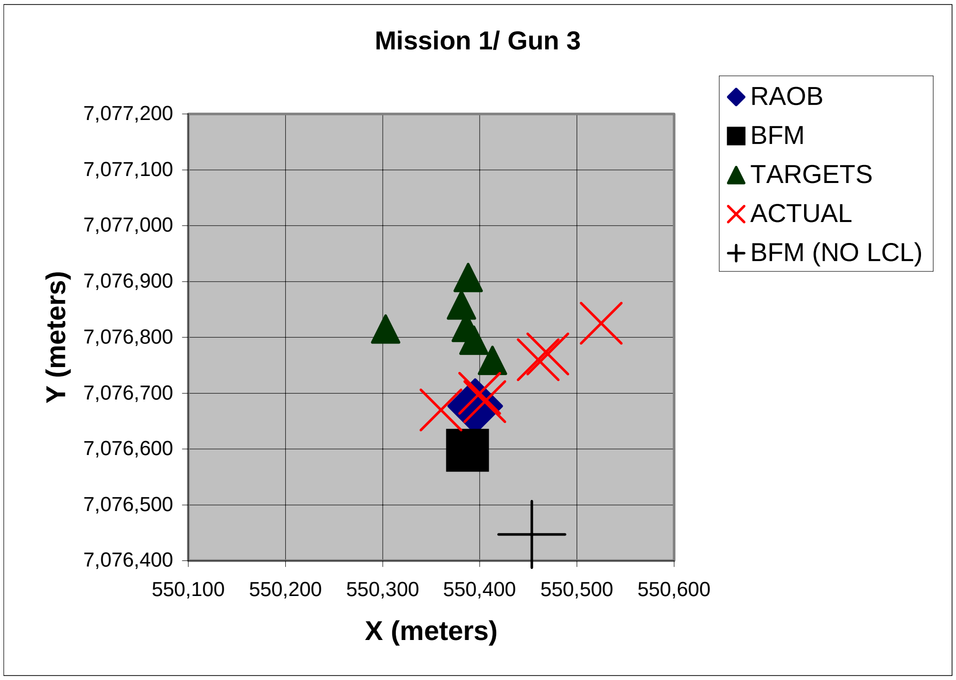
The RMSE values for temperature, pressure, and wind speed appear to be rather trivial. The wind direction RMSEs are more considerable, ranging from about 30^0 to 45^0. The question becomes, how significant are these differences (particularly for wind direction) to the SADARM targeting accuracy? The following four sections address this question by comparing MRMD values for GTRAJ3 simulations using both RCMMs and BCMMs.

6.2 Mission 1

Six guns fired volleys during Mission 1. Gun 3 was the most closely aimed at the targets; therefore, this particular plot was selected as an example. Figure 8 shows the actual and simulated impacts of this aiming information. This information shows that the performance of the BFM is greatly enhanced by having a local RAOB included in its initialization data set. This observation was clearly evident in all of the BFM-based GTRAJ3 simulations. In the figure, the square labeled "BFM" is the

GTRAJ3 simulated impact point for which the local RAOB was used when the BFM was initialized to produce the BCMM. The "+" symbol shows the simulated impact when its BCMM did not have a local RAOB incorporated into the BFM initialization (labeled "BFM [NO LCL]").

Figure 8. Mission 1 SADARM and simulated impacts.



The BFM impact was only about 75 m south of the RAOB. After depriving the BFM of local RAOB information, the GTRAJ3 simulation impacted at the "+" symbol, about 150 m farther to the south-southeast. It should be noted that the relative positioning of the RAOB, BFM, and BFM (NO LCL) simulated impacts was *almost* identical from one firing to the next. Because the guns were not aimed at exactly the same azimuth/elevation angles, the GTRAJ3 simulated trajectories were affected by the input Met in slightly different ways. The differences were so minute, however, they are imperceptible when visually comparing the plots. Although Gun 1 and Gun 3 were aimed differently and the simulated impacts were several hundred meters from the targets, the relative positioning between the three simulations was almost identical to that of figure 8.

Table 3 summarizes the MRMD data from Mission 1. The "RAOB-TGT" column shows the MRMD values from the RAOB-simulated impact to each of the six targets. (For example, the *mean* distance from the RAOB-simulated impact out of Gun 3 to the six targets was 141 m). As discussed in section 4, this column's MRMD values indicate which guns were aimed closest to the targets. The corresponding values from the BFM simulation to the targets are shown in the next column[§§].

The MRMD values from the RAOB simulation to each of the actual RAID impacts are shown in the *"RAOB-ACT"* column. (For example, the *mean* distance from the RAOB-simulated impact out of Gun 3 to the RAID impacts was 82 m.) The corresponding values from the BFM simulation to the RAID impacts are shown in the far-right column.

Table 3. Mission 1 MRMD values

		Mission 1, MRMD (m)		
Gun no.	**RAOB-TGT**	**BFM-TGT[§§]**	**RAOB-ACT**	**BFM-ACT**
1	360	368	193	261
2	232	283	178	212
3	141	218	82	150
4	347	419	110	181
6	271	277	96	138
7	125	185	106	129

The "RAOB-TGT" MRMD values ranged from 125 to 360 m. Had the aiming been closer to the targets (that is, the RAOB simulations hitting closer to the targets), the comparisons between RAOB and BFM could very well have come out differently. At best then, the MRMD values between the simulations and the actual impacts were somewhat inconclusive. However, those results are described in the following paragraph.

The BFM simulations were farther from the actual impacts than the RAOB simulations, for each of the Mission 1 guns. However, for three of the guns (2, 6, and 7), the difference was relatively small (34, 44, and 23 m, respectively). For Gun 7, which was the "best aimed" (MRMD to targets of 125 m), the BFM MRMD to the actual impacts was only 23 m greater than that of the RAOB.

[§§] The MRMD values in this column have no bearing on the analysis, but are included for comparison.

6.3 Mission 2

Mission 2 consisted of seven firings. Three of the seven guns were aimed reasonably close to the targets (again, as determined by the GTRAJ3 simulation using the RCMM). Figure 9 depicts the results from Gun 2:

Figure 9. Mission 2 SADARM and simulated impacts.

The diamond symbol, indicating the GTRAJ3 RAOB impact simulation, fell almost directly on one of the targets. The BFM Met simulation produced an impact about 100 m to the north-northwest, near the center of the target array. Without including the local RAOB in the BFM initialization, the BCMM produced an impact about 300 m to the NE.

Table 4 lists the MRMD values resulting from Mission 2.

Table 4. Mission 2 MRMD values

	Mission 2, MRMD (m)			
Gun no.	RAOB-TGT	BFM-TGT	RAOB-ACT	BFM-ACT
1	120	66	74	101
2	96	68	144	82
3	114	110	89	94
4	167	108	102	84
6	98	178	139	157
7	273	252	175	219
9	193	309	133	148

The MRMD for two of the firings was *less* for the BFM simulations than for the RAOB (for Guns 2 and 4) and essentially the same for Gun 3. The MRMD for the BFM most exceeded that of the RAOB for Gun 7 (219 versus 175 m). It was interesting to note that Gun 7 was aimed farther from the targets as compared to the other guns, since its "RAOB-TGT" MRMD was 273 m.

Overall the BFM gave its best performance for Mission 2 since its MRMD values were less than those using the RCMM for two of the guns, and almost equal for a third.

6.4 Mission 3

The analysis for Mission 3 was complicated by a change in the way the guns were aimed. According to a note in the IOT&E data file provided by the Program Office, the Standard Atmosphere was input as the Met data for each of the Mission 3 firings. The Standard Atmosphere incorporates worldwide mean values of temperature and density, and the wind is set to zero at all levels. Figure 10 shows the full set of RAID impacts as well as the GTRAJ3 simulated impact points using only the Standard Atmosphere.

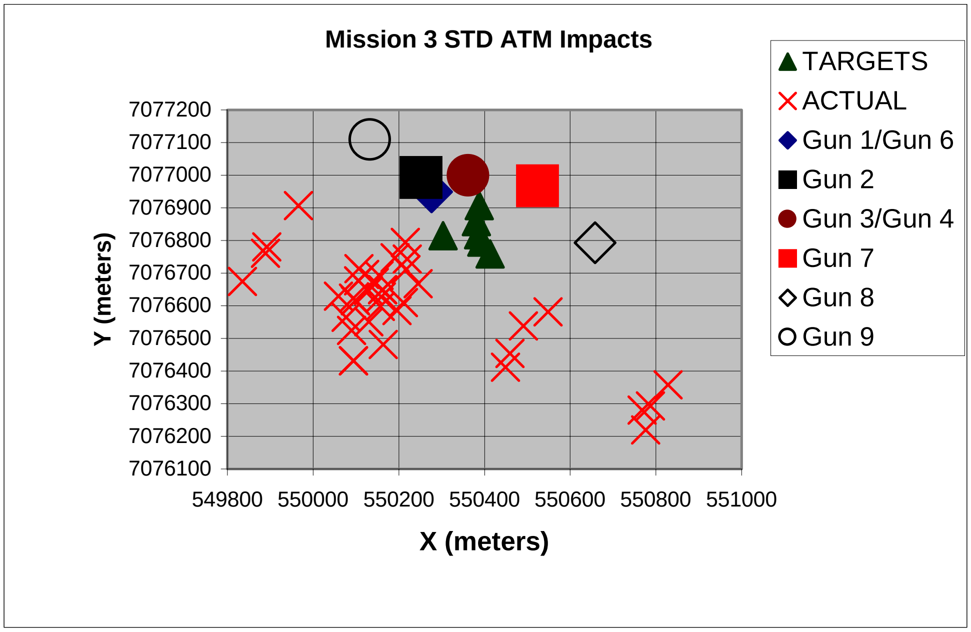


Figure 10. Mission 3 Standard Atmosphere simulated impacts.

Gun 1 and Gun 6 simulated impacts have been combined, as have Gun 3 and Gun 4, since for these firings the simulated impacts were so close as to be indistinguishable. Only Guns 3 and 4 were aimed relatively close to the targets, given the Standard Atmosphere assumption that there was no wind. Guns 7, 8, and 9 were aimed a substantial distance from the target array.

In reality, of course, there was wind. During Mission 3, the wind in the lowest 1000 m AGL was from the north-northeast. This "tail wind" apparently carried the rounds farther downrange, causing them to overshoot the targets.

Table 5 lists the MRMD data for Mission 3. The STD ATM-TGT column shows the MRMD values from the Standard Atmosphere GTRAJ3 impacts to the targets. Again, this column was included since the guns were aimed using the Standard Atmosphere.

Table 5. Mission 3 MRMD values

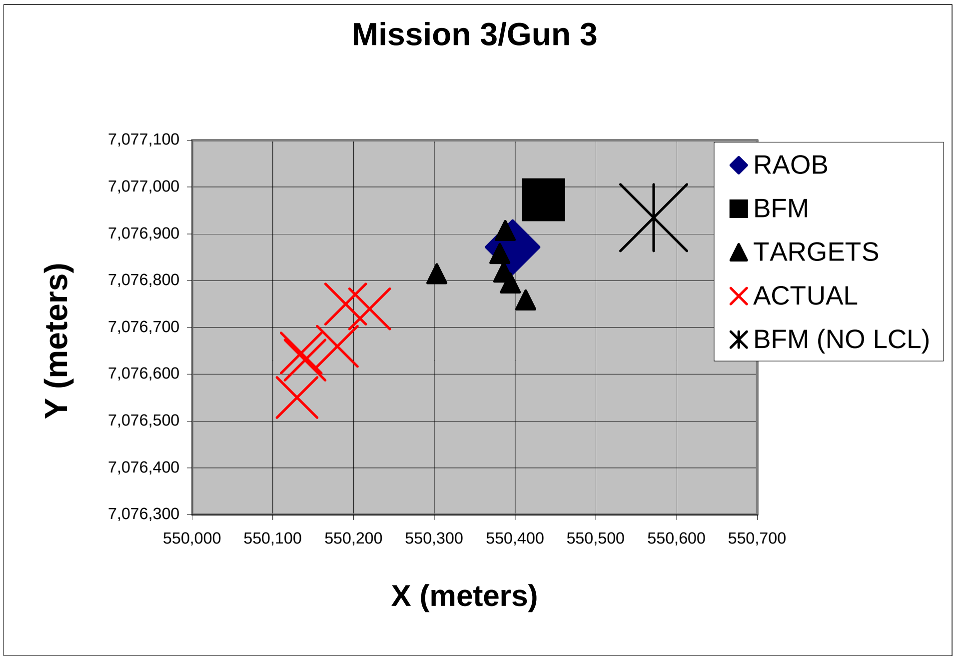
	Mission 3, MRMD (m)				
Gun no.	**STD ATM TGT**	**RAOB-TGT**	**BFM-TGT**	**RAOB-ACT**	**BFM-ACT**
1	166	109	102	278	384
2	213	137	187	266	366
3	187	80	162	314	412
4	177	70	140	339	438
6	157	77	148	299	412
7	208	183	257	571	671
8	286	360	376	265	377
9	377	267	297	300	402

NOTE:

STD ATM TGT Standard Atmosphere Target

The GTRAJ3 simulations for Gun 1 are depicted in Figure 10.

Figure 11. Mission 3 SADARM and simulated impacts.



Both the BFM and the RAOB CMMs accounted for the wind direction correctly enough to align the simulations with the line of RAID impacts. Neither the RAOB nor the BFM totally accounted for the wind speed in the target area; therefore, both simulations fell short of the actual impacts. According to Table 5, the actual impacts' MRMD for the BFM averaged about 100 m greater than the RAOB.

6.5 Mission 5

The impact simulations for the best-aimed gun in Mission 5 are shown in figure 12.

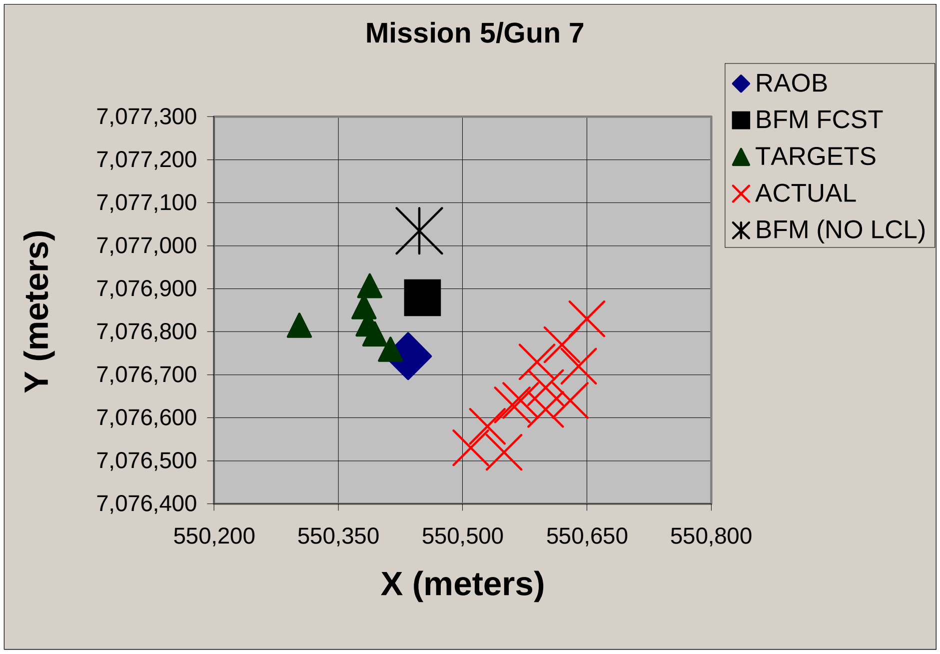


Figure 12. Mission 5 SADARM and simulated impacts.

Although Gun 7 was aimed very close to the targets based upon the gun-area RAOB, there was clearly a different wind in the target area that carried the rounds more towards the southeast. This scenario held true for the other four guns that participated in Mission 5. Unfortunately the target area RAOB terminated shortly after launch so it is impossible to know exactly what happened there.

The MRMD values, simulations to targets, were about 100 m greater for the BFM than for the RAOB (table 6). Once again, the gun aimed closest to the targets (Gun 7 with a "RAOB-TGT" MRMD of 91 m) produced the least difference between RAOB and BFM (200 versus 274 m).

Table 6. Mission 5 MRMD values

	Mission 5, MRMD (m)			
Gun no.	**RAOB - TGT**	**BFM-TGT**	**RAOB-ACT**	**BFM-ACT**
1	175	180	167	269
3	110	209	177	291
4	114	208	203	320
6	139	201	134	211
7	91	110	200	274

6.6 Simulated Impact Point Comparisons

Comparing MRMDs to the actual impacts is but one way to determine how well the BFM Met messages performed against their RAOB Met message counterparts. Since the RCMMs more accurately represented the atmosphere for most of the IOT&E firings, we decided to compare BCMMs to the RAOB-based Met messages via the GTRAJ3 simulations. In other words, we calculated how far apart the RAOB- and BFM-produced GTRAJ-simulated impact points were separated. While this has no direct validity in determining which type of CMM produced the most accurate Met data for aiming the SADARM rounds, it does tell something about how close the BFM came to the RAOB-data. These data are shown in Table 7. On average, the simulated impact points of the RAOB-produced output were 113 m from the BFM-produced impact points.

Table 7. Distances from RAOB to BFM-simulated impact points

Mission	**No. of guns**	**Range of separations (m)**	**Mission AVG distance (m)**
1	6	77-80	79
2	7	121-126	123
3	8	104-130	118
5	5	125-138	130

---

7. Summary and Conclusions

Data from the SADARM IOT&E firings in Alaska provided the opportunity to compare trajectory simulations using current RAOB-based Met messages to the future capability of using forecast model-based messages. The goal of the study was to determine if there was value-added to the firing calculations by using BFM Met data (since it was expected to be more representative of the entire trajectory than data supplied only by a gun-area RAOB). Because there was variability in the aiming points for the various missions, the results of the GTRAJ3 simulations could not be considered highly conclusive. Thus, more analysis with data from follow-up firings is needed. An additional goal of the study was to use GTRAJ3 simulations to quantify the differences between RAOB-based and BFM-based CMMs.

For the four SADARM missions studied (ranges of slightly less than 20 km), GTRAJ simulations proved that the BFM performed favorably to the RAOBs in representing the true atmosphere at the time of each SADARM firing. Using MRMD between actual impact points and the RAOB and BFM-simulated impact points, the RAOB method generally outperformed the BFM method. However, this conclusion is not highly definitive given the limited sample size and difficult data collection conditions of the IOT&E firings, as well as the varying aiming accuracies among the different guns. The best test for checking how the BFM compared directly to the RAOB data is to calculate the differences between simulated impact points for each method. For all four missions, the average difference was just 113 m, indicating that the BFM did at least an adequate job of reproducing the RAOB Met.

The BFM performed less effectively than the gun RAOBs for several reasons. First, it has been proven in earlier studies [1,5] that under relatively light and variable wind conditions from the surface to apogee, and for firing ranges of 20 km or less, a local forecast model will generally not outperform an actual gun-area RAOB. Next, one of the required BFM input parameters is "surface albedo"[***]. The value of the surface albedo input to the BFM can have a marked effect on the ability of the model to correctly predict temperature and wind characteristics. Portions of the high terrain just south of the firing range were snow or glacier covered, but the extent and brightness of the snow fields were unknown. Thus, the accuracy of the BFM might very well have suffered due to possible inaccuracies in this parameter. Finally, as was mentioned in section 3, the BCMMs were derived from 1-h forecasts. It is unlikely that such a short model forecast could be more accurate than a very recent RAOB. In fact, subsequent SADARM analyses from Yuma Proving Ground, AZ (YPG) have suggested that the BFM only offers any real advantage when the RAOBs are at least 3 h old. In summary, these factors plus the relatively benign Met conditions, the short firing range, and occasionally inaccurate aiming solutions for the IOT&E missions, all tended to work against the BFM's accuracy. It was encouraging then that the model performed as well as it did, as compared to the RAOBs.

Follow-up SADARM firing data collections from the Reliability Determination/Assurance Program and the Limited User Test missions at YPG in January and April to May 2000 have been accomplished with much tighter and more thorough procedures. Studies will continue on these data which will lead to publishing technical reports on three topics: 1) actual Met data depictions as predicted by the BFM; 2) specific GTRAJ3 results from the data supplied by the SADARM OPM-ARMS and 3) Circular Error Probable depictions comparing the gun location RAOB Met to the BFM Met to show SADARM effectiveness calculations. These studies using the YPG databases are expected to more conclusively compare BFM performance against standard gun-area, RAOB-based CMMs. Preliminary results indeed have shown significant value-added by using the BFM.

[***] This value is a measure of the capacity of the Earth's surface to reflect incoming short-wave solar radiation, ranging from 0.0 to 1.0. For example, very white, fresh, bright snow fields have a value that approaches 1.0. Dark green stands of trees, or even glacial flows, have much lower values.

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4. Henmi, T. and R. E. Dumais, *Description of the Battlescale Forecast Model* (U), U.S. Army Research Laboratory, White Sands Missile Range, NM, ARL-TR-1032, 1996. (UNCLASSIFIED)
5. Blanco, A.,E., J. B. Spaulding, and N. H. Kilmer, *Analysis of the Computer-Assisted Artillery Meteorology (CAAM) Results from a Live-Fire Exercise* (U), U.S. Army Research Laboratory, White Sands Missile Range, NM, ARL-TR-1000, April, 1996. (UNCLASSIFIED)

Acronyms

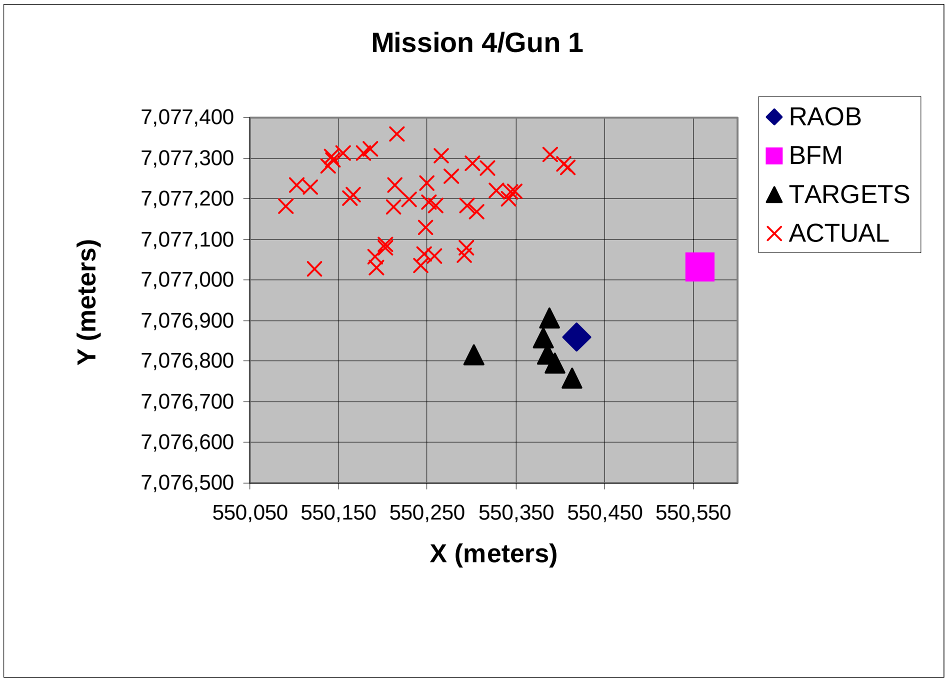
3-D	three deminsional
4-D	four deminsional
3DOBJ	3-Dimensional Objective
AGL	Above Ground Level
ARDEC	Armament Research Development and Engineering Center
ARL	U.S. Army Research Laboratory
BCMM	BFM-based Computer Met Message
BCS	Battery Computer System
BFM	Battlescale Forecast Model
CMM	Computer Met Message
DTED	Digital Terrain Elevation Data
EFP	Explosively Formed Penetrator
EOM	equations of motion
GTRAJ3	General Trajectory Model – Version 3
HOTMAC	Higher Order Turbulence Model for Atmospheric Circulations
IOT&E	Initial Operational Test and Evaluation
LUT	Limited User Test
Met	meteorlogical
MET-TALL	Meteorology-Target Area Low Level
MRMD	Mean Radial Miss Distance
MSL	Mean Sea Level
NOGAPS	Navy Operational Global Atmospheric Prediction System
OPM-ARMS	Office of the Program Manager, Artillery Munitions Systems
RAID	Ram-Air Inflated Decelerator
RAOB	Rawinsonde (Radio wind Sounding) Observation
RCMM	RAOB-based Computer Met Message

RDAP	Reliability Determination/Assurance Program
RMD	Radial Miss Distance
RMSE	root mean square error
SADARM	Sense and Destroy Armor
TE	True East
TN	True North
TS	True South
USGS	United States Geological Survey
UTC	Universal Time Coordinate
UTM	Universal Transverse Mercator
VRP	Vortex Ring Parachute
YPG	Yuma Proving Ground

Appendix. Initial Operational Test and Evaluation Mission 4 Data Summary

Mission 4 of the Sense and Destroy Armor (SADARM) Initial Operational Test and Evaluation (IOT&E) was not included in the primary study since a thunderstorm "microburst" in the target area (for which the winds exceeded 25 ms^{-1} in the levels near the surface) rendered its data invalid. Figure A-1, a plot from this mission-day, is a representation of the firing situation during Mission 4.

Figure A-1. Mission 4 SADARM and simulated impacts.



The impacts from all of the participating guns have been plotted to show that even the closest hit is about 200 m to the northwest of the targets. Gun 1 was aimed closest to the targets (indicated by the "RAOB" symbol) although the other six participating guns were similarly fired. Figure A-1 points out that a brief and highly localized Met event such as a microburst can neither be detected by a Rawinsonde (radio wind sounding) Observation (RAOB) that is released many kilometers distant nor can it be forecast by a mesoscale model such as the Battlescale Forecast Model.

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