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Can Simple Models Predict Air Combat Results?

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This paper investigated the potential value of models and simulations to predict the results of aerial engagements. Three historical scenarios from 1965 to 1991 were examined. A modified salvo model and an air combat simulation were compared with real-world data from these scenarios. These models and simulations were also used to examine a hypothetical future scenario to determine potential insights. The results of this comparison indicated that even simple models and simulations can provide useful metrics. Care must be taken, however, to account for sufficient real-world effects. The use of multiple models and/or a number of study runs can also help improve predictive capability. Notably, even where real-world data are unavailable, as in the hypothetical future scenario, the predictions of combined modeling and simulation runs generated interesting results and highlighted areas for further study.

I. Introduction

THE purpose of this paper is to investigate the potential value of models and simulations to predict the results of aerial engagements. We will examine three historical scenarios from 1965 to 1991. A modified salvo model and an air combat simulation will be compared with real-world data from these scenarios. These models and simulations will also be used to examine a hypothetical future scenario to see what insights can be gained.

The subsequent sections of the paper are formatted as follows:

1) Section II outlines the metrics used to compare modeling and simulation predictions against real-world results.

2) Section III outlines assumptions simplifying the complexity of an actual aerial engagement to a manageable level.

3) Section IV explains the modified salvo model and air combat simulation employed for this study.

4) Section V describes our historical scenarios and hypothetical engagement.

5) Sections VI, VII, VIII, and IX focus on modeling and simulation analysis results.

6) Section X summarizes the study conclusions.

Please note that all of the data used for these models come from unclassified, open-source references. The results and conclusions presented here are the author's views alone and do not reflect the position of Lockheed Martin.

II. Metrics

We will use the following metrics to compare our models to real-world data: 1) exchange ratio, 2) percentage of radio-frequency- (RF) guided missile kills, 3) percentage of infrared- (IR) guided missile kills, and 4) percentage of cannon kills.

Our first metric, an exchange or kill ratio, is a measure of the number of aircraft shot down by each side in the combat, blue and red. We will use the following formula to calculate the exchange ratio in our air combat engagements:

$$\text{Exchange ratio metric: exchange ratio} = \#\text{of blue aircraft hit}/\#\text{of red aircraft hit} \tag{1}$$

For this definition of the exchange ratio metric, values less than 1.0 indicate a favorable outcome for blue forces, meaning that more red aircraft were destroyed than blue aircraft. Exchange ratios greater than 1.0 indicate that more blue aircraft were lost than red aircraft.

Each aircraft destroyed in an engagement will be assigned a value of 1.0, while each aircraft damaged in an engagement will be counted as 0.5. As an example, if during an engagement, blue has one aircraft shot down and one aircraft damaged while red has three aircraft shot down the resulting exchange ratio would be

$$\text{Example exchange ratio} = 1.5 \text{ blue aircraft hit}/3 \text{ red aircraft hit} = 0.5$$

The remaining metrics will allow us to determine how each aircraft was damaged or destroyed, either by RF- and IR-guided missiles or by cannon fire. We will use the metrics generated by our models for a comparison to data obtained from the three scenarios described in Sec. V.

III. Assumptions

Every model or simulation contains simplifications from the real-world system(s) being represented. These simplifications enable generating estimates of real-world system behavior without having to test the actual system for every conceivable situation. Modeling and simulation enables us to predict how a system will perform even if in reality doing so would be cost-prohibitive or even dangerous.

We will make the following simplifying assumptions for our air combat models, which are described in Sec. IV:

1) Sorties will consist of fighter sweeps for both blue and red, where fighters from one side engage fighters from another side without escorting any other aircraft (such as strike aircraft).

2) Each engagement will consist of four blue aircraft against six red aircraft with blue forces fighting in a mutually supporting formation while the red aircraft are split into three pairs of fighters, each consisting of a flight lead and wing man.

3) Although both of our air combat models can accommodate varying numbers of aircraft involved in an engagement, we will focus on a scenario consisting of four blue versus six red fighters to represent a typical engagement while limiting Monte Carlo replications to a manageable number compared with a series of M versus N aircraft engagements.

4) For historical scenarios, we will compare modeling and simulation engagement results to overall campaign metrics despite differences in numbers of aircraft, sortie types, or pilot training/combat experience during actual combat.

5) Models and simulations will not account for differences in pilot training and/or combat experience between blue and red forces.

6) As discussed in Sec. IV, our modified salvo model will not account for aircraft damage while the higher-fidelity air combat simulation will include damage effects.

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Fig. 1 Sample aerial engagement formations and placement for opposing forces.

7) With the exception of the Persian Gulf scenario described in Sec. V.C, no air controllers are assumed for either blue or red forces, and each side employs onboard sensors to detect hostile aircraft.

Figure 1 provides a representative example of the initial placement for the blue and red aircraft. Per the air combat simulation described in Sec. IV.B, the relative locations and ranges between the forces are randomized for each of the Monte Carlo study runs.

IV. Models

We will examine two different simulations in our examination of aerial combat engagements. The first will be a modified salvo model generated using spreadsheets while the second will be a more complex air combat representation based on the *Flight Commander 2* simulation written by Charles Moylan and published by the Avalon Hill Game Company.

A. Modified Salvo Model

The salvo model developed by Captain (retired) Wayne Hughes was intended to examine missile combat between two opposing naval fleets with a number of ships labeled "*A*" and "*B*", respectively. The Hughes salvo calculations, indicated as Eqs. (2) and (3), include terms for salvo size, accurate missiles launched, defensive power, and number of hits required to put a ship out of action [1]:

Hughes salvo model equation for force "A" attrition: ΔA

$$= (\beta B - a_3 A)/a_1 \tag{2}$$

Hughes salvo model equation for force "B" attrition: ΔB

$$= (\alpha A - b_3 B)/b_1 \tag{3}$$

In the preceding equations, the ΔA and ΔB terms refer to the losses incurred by two opposing fleets, with a number of ships A and B, respectively. The number of accurate missiles launched in a salvo are represented by α and β. Defensive power for each ship is represented by a_3 and b_3, while the number of hits to successfully put a ship out of action is determined by a_1 and b_1.

We will incorporate a number of adaptations to the Hughes salvo model to examine air combat instead of naval fleet engagements. In this use of the salvo equations, the two opposing forces (blue and red), have four and six aircraft, respectively, as described in Sec. III. We will assume that only one hit is required to put an aircraft out of action, thus setting both a_1 and b_1 equal to one. Accurate missiles launched, α and β, will be a function of sensor capability, aircraft payload, missiles launched per target, aircraft maneuverability, and missile kill probability (P_K). Aircraft defensive power will be assumed based on maneuverability as well as RF- and IR-countermeasure capabilities. This aircraft defensive factor will reduce the effectiveness of incoming missile salvos.

A second modification to the salvo model will allow generating either deterministic scenario results based on fixed values for the parameters in Eqs. (2) and (3) or varying output over a number of Monte Carlo replications. To extend the model from deterministic to Monte Carlo results we will incorporate random number multiplier factors for both the number of accurate missiles launched and aircraft defensive power parameters. Thus, each time we run the salvo model, the results will vary based on the random number draws, thereby enabling a range of predicted outcomes to be averaged.

Finally, we will also adapt our modified salvo model to address employment of different weapons based on engagement range. Specifically, we will assume four combat phases for the modified salvo model in the following sequence: 1) RF-guided missile engagement, 2) IR-guided missile engagement, 3) cannon engagement, and 4) disengagement.

B. Air Combat Simulation

The *Flight Commander 2* simulation allows the user to vary a number of input parameters for both attacking and defending forces. These inputs include: 1) number and type of aircraft, 2) weapon type and load, 3) number of targeting and electronic countermeasure pods, 4) fuel load, 5) range to home base (very short, short, medium, long, or very long), 6) mission type, 7) presence of air combat controllers, and 8) weather conditions (clear, cloudy, or night).

The air combat simulation represents the movement of each aircraft in place of the four-stage engagement phase simplification used for the modified salvo model. The air combat simulation in addition accounts for aircraft damage, whereas our modified salvo model assumes any hit results in an aircraft kill.

The *Flight Commander 2* simulation allows human-versus-human, human-versus-computer, or computer-versus-computer engagements. Our study runs will use the computer-versus-computer option with both sides set to identical skill levels. This will remove any potential bias as a result of different abilities for the two opposing forces.

V. Scenario Description

We will examine the predictive capability of our modified salvo model and air combat simulation in three historical scenarios: 1) South East Asia (Vietnam) 1965–1972, 2) Falklands Islands 1982, and 3) South West Asia (first Persian Gulf War) 1991.

In addition, we will use the modified salvo model and air combat simulation to examine a hypothetical scenario. This will enable us to see if they can provide insights into future air combat engagements.

A. South East Asia 1965–1972

One of the primary aircraft flown by the United States over Vietnam was the F-4 Phantom 2, as illustrated in Fig. 2. The F-4 served in both air-to-air and air-to-ground combat roles, but our focus will be on aerial engagements against North Vietnamese MiG fighters. According to a Wikipedia entry, the U.S. Air Force (USAF) lost 33 F-4 Phantom 2s to MiG engagements while downing a combined total of 107.5 MiG-17, MiG-19, and MiG-21 North Vietnamese fighters [2]. Based on our exchange ratio formula, as defined in Sec. II, these data provide the following result:

$$F\text{-4 to MiG exchange ratio} = 33F\text{-4}/107.5\,\text{MiG} = 0.31$$

We will see how our modified salvo model and air combat simulation compare to real-world results. Our model engagement will consist of a fighter sweep pitting four F-4C Phantom 2s against six MiG-21 Fishbeds. We will assume each Phantom carries four AIM-7E Sparrow radar-guided missiles and four AIM-9B heat-seeking Sidewinder missiles, but does not have an internal gun or external cannon pod. The MiG-21s carry two AA-2 IR-guided missiles and an internal cannon. Assumed missile kill probability (P_K) values are

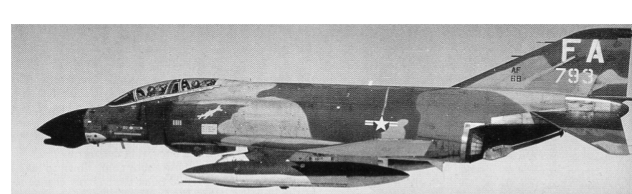

Fig. 2 USAF Mcdonnell Douglas F-4D Phantom 2 in South East Asia (courtesy of Albert Piccirillo).

Table 1 Vietnam air-to-air missile kill probabilities

Missile	Kill probability (P_K)
RF-guided AIM-7E Sparrow	0.35
IR-guided AIM-9B Sidewinder	0.45
IR-guided AA-2	0.40

Table 2 Falklands islands air-to-air missile kill probabilities

Missile	Kill probability (P_K)
IR-guided AIM-9L Sidewinder	0.70
RF-guided R.530	0.35
IR-guided Magic-1	0.60

listed in Table 1 [3]. For consistency, we will use these P_K values from the air combat simulation in the modified salvo model as well.

The radar-guided AIM-7 Sparrow accounted for approximately 57% of the USAF air-to-air missile kills in the Vietnam conflict, while the IR-guided AIM-9 Sidewinder accounted for about 38%. The radar-guided AIM-4 Falcon was responsible for the remainder of the USAF air-to-air missile kills [4]. Based on the Vietnam conflict missile kill percentages and our exchange ratio of 0.31, we would expect our scenario of four F-4s versus six MiG-21s to yield 1.8 MiG-21s destroyed by the AIM-7 Sparrow and 1.2 MiG-21s destroyed by the AIM-9 Sidewinder for each F-4 lost.

B. Falklands Islands 1982

During the Falklands Islands conflict between the United Kingdom (UK) and Argentina in 1982, the UK was forced to rely on Sea Harrier aircraft aboard two Royal Navy aircraft carriers to provide air cover. Argentinean air forces were equipped with French-built Mirage 3Es, Mirage 5s, Super Etendards and the U.S.-built A-4 Skyhawk. The ensuing aerial combat resulted no British losses against 31 Argentinean aircraft shot down for an exchange ratio of 0.00.

For our Falklands air combat scenario we will assume four British Sea Harrier aircraft flying against six Argentinean Mirage 3Es. The Sea Harriers will carry four AIM-9L IR-guided Sidewinders and internal cannons. Each Argentinean Mirage will carry one Matra R.530 radar-guided missile, two Magic-1 IR-guided missiles, and an internal cannon. Assumed missile P_K values are provided in Table 2 [3].

The newer AIM-9L Sidewinders carried by the British Harriers enabled them to engage hostile aircraft from all target azimuths without maneuvering to the rear of the target to acquire the hot jet exhaust. This advantage over older rear-aspect IR-guided missiles would enable the British to achieve 24 of their 31 air-to-air kills in the Falklands with the AIM-9L Sidewinder [4]. The Harrier's 30 mm cannon accounted for the other 7 seven kills.

C. Persian Gulf 1991

After the Iraqi invasion of neighboring Kuwait on 2 August 1990, the United States helped organize an Allied coalition to prevent further Iraqi aggression and ultimately to liberate Kuwait. Once Allied operations began on 17 January 1991, air strikes on communication nodes, command and control sites, and airfields hindered the Iraqi ability to mount effective air operations. Allied aircraft quickly gained air supremacy over the skies of Kuwait and Iraq. A total of 43 Iraqi aircraft were destroyed in aerial combat with no Allied losses [5]. This results in an exchange ratio of 0.00, based on our formula defined in Sec. II.

Our Persian Gulf scenario will feature four USAF F-15C Eagles versus six Iraqi MiG-25 Foxbat A fighters. Each Eagle will be outfitted with four radar-guided AIM-7M Sparrow missiles, four AIM-9M heat-seeking Sidewinder missiles, and an internal 20 mm cannon. The MiG-25s will carry two RF-guided AA-6 Acrid and two IR-guided AA-8 Archer missiles. Table 3 lists assumed P_K values for each of the missiles employed in this scenario [3].

Table 3 Persian Gulf air-to-air missile kill probabilities

Missile	Kill probability (P_K)
RF-guided AIM-7M Sparrow	0.60
IR-guided AIM-9M Sidewinder	0.85
RF-guided AA-6 Acrid	0.40
IR-guided AA-8 Aphid	0.55

Another advantage enjoyed by Allied forces in the Persian Gulf conflict was a command and control capability that Iraqi pilots were denied. We will investigate the effects of blue air controllers on engagement results, as described in Sec. VIII.

D. Hypothetical Future Scenario

We will also examine one hypothetical scenario, though there will not be any real-world comparison data. This scenario will enable us to determine any insights that may be gleaned regarding the future of air combat engagements. Our hypothetical scenario will consist of four Lockheed Martin F-22A Raptors, as illustrated in Fig. 3, versus six Sukhoi Su-27 Flankers. Our hypothetical scenario will differ from earlier engagements in that the F-22A design incorporates stealth features that will increase the aircraft defensive power described in Sec. IV. Both sides will also employ extended range "fire-and-forget" radar-guided missiles that do not require the launching aircraft to continuously illuminate the target with onboard radar.

We will assume the F-22s carry four AIM-120 advanced medium range air-to-air missile (AMRAAM) fire-and-forget radar-guided missiles, four AIM-9X Sidewinder heat-seeking missiles, and an internal cannon [3]. The Su-27s will be outfitted with four RF-guided AA-12 Vympel fire-and-forget missiles, four IR-guided AA-11B missiles, and an internal cannon. Table 4 lists the assumed missile kill probabilities [3].

VI. South East Asia Scenario Results

We will first examine results from our modified salvo model. Based on assumed values for the input parameters, we see that our model predicts results listed in Table 5. When we compare the model predictions to real-world results we see a dramatic difference in the exchange ratio. In addition to the simplifications imposed by our modeling assumptions in Sec. III this outcome highlights a limitation in our preliminary model because we did not account for U.S. rules of engagement (ROE) in South East Asia.

During much of the Vietnam conflict, U.S. pilots operated under strict ROE that prevented them from engaging targets without first having visual identification confirming that an aircraft was hostile.

Fig. 3 USAF Lockheed Martin F-22A Raptor (courtesy of the author).

Table 4 **Hypothetical scenario air-to-air missile kill probabilities**

Missile	Kill probability (P_K)
RF-guided AIM-120 AMRAAM	0.65
IR-guided AIM-9X Sidewinder	0.95
RF-guided AA-12 Vympel	0.55
IR-guided AA-11B Archer	0.75

Table 5 **South East Asia deterministic modified salvo model results without ROE restrictions**

Analysis metric	Deterministic model prediction	Real-world data
Exchange ratio	0.00	0.31
AIM-7E missile kill ratio	0.67	0.57
AIM-9B missile kill ratio	0.33	0.38

Table 6 **South East Asia deterministic modified salvo model results with ROE restrictions**

Analysis metric	Deterministic model prediction	Real-world data
Exchange ratio	0.25	0.31
AIM-7E missile kill ratio	0.75	0.57
AIM-9B missile kill ratio	0.25	0.38

These rules were put in place to reduce friendly fire incidents. The unintended consequence was to reduce the engagement range of F-4 Phantoms equipped with radar-guided AIM-7E Sparrow missiles. The result was an increase in the number of close-range dogfights where the initial lack of an internal cannon put the Phantoms at a disadvantage. If we adjust our model inputs to account for ROE restrictions we see results as illustrated in Table 6.

A deterministic model can provide insights into expected real-world behavior but conducting a number of replications, each with different random number draws, can provide a range of expected

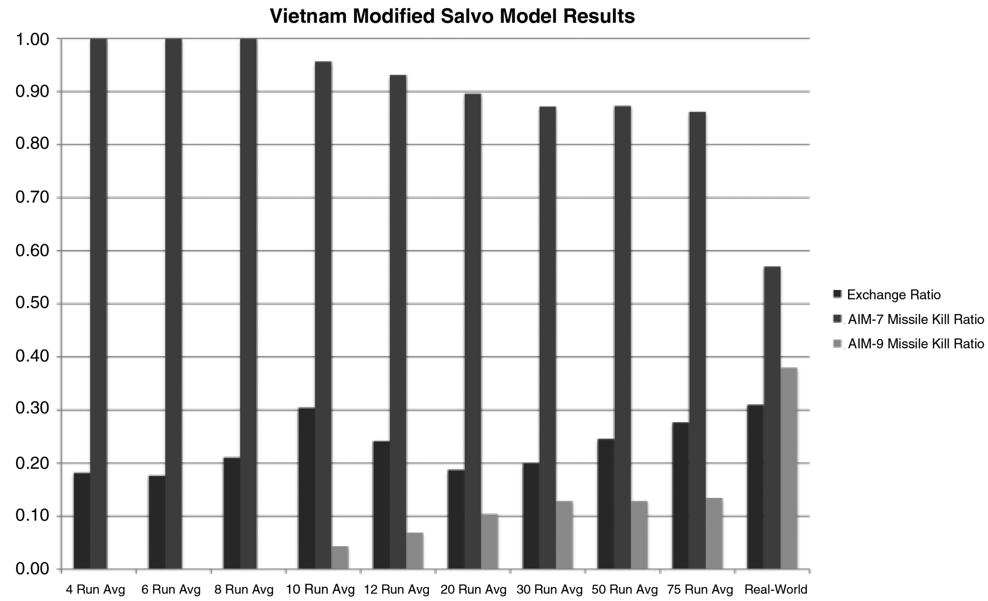

Fig. 4 South East Asia modified salvo model Monte Carlo results.

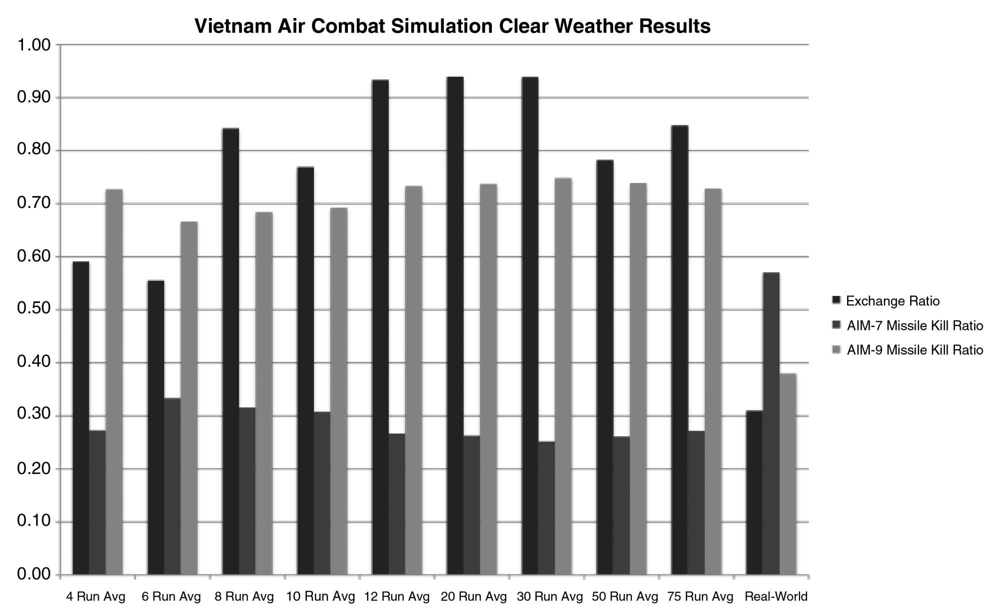

Fig. 5 South East Asia air combat simulation Monte Carlo results.

Table 7 Falklands deterministic modified salvo model results

Analysis metric	Deterministic model prediction	Real-world data
Exchange ratio	0.00	0.00
AIM-9L missile kill ratio	0.67	0.77
Cannon kill ratio	0.33	0.23

results. We can average these Monte Carlo runs to provide a probability of most likely outcomes. Figure 4 provides averaged results from our modified salvo model for 4 to 75 replications.

As the number of Monte Carlo runs increases the AIM-7 and AIM-9 missile kill ratios begin to trend in the direction of the observed real-world values. The predicted exchange ratio also shows a trend approaching the USAF F-4 to North Vietnamese MiG exchange ratio of 0.31. Prior threat susceptibility analyses have employed as many as 900 Monte Carlo runs per scenario to predict threat susceptibility performance. In this study 75 replications per scenario should be sufficient to gain useful insights.

Now we will turn to the results of the air combat simulation. Comparisons of scenario runs from 4 to 75 replications are provided as Fig. 5. Note that the air combat simulation predicts a higher exchange ratio than the modified salvo model or the real-world data. This is likely a result of our simulation assumption of equal pilot training levels for both blue and red. We also observe that the air combat simulation results indicate a higher percentage of AIM-9B Sidewinder missile kills compared with the modified salvo model.

VII. Falklands Islands Scenario Results

We will next examine the 1982 Falklands Islands scenario pitting six Argentinean Mirage 3Es against four British Royal Navy Harriers. Table 7 outlines the predicted results of a deterministic modified salvo model compared with real-world results. Note that the deterministic model predicts the 0.00 exchange ratio observed in 1982, indicating the advantage conferred by the all-aspect fire-and-forget AIM-9L Sidewinder. The model also predicts a majority of AIM-9L missile kills compared with cannon kills, but the missile percentages are lower than those observed in the Falklands campaign.

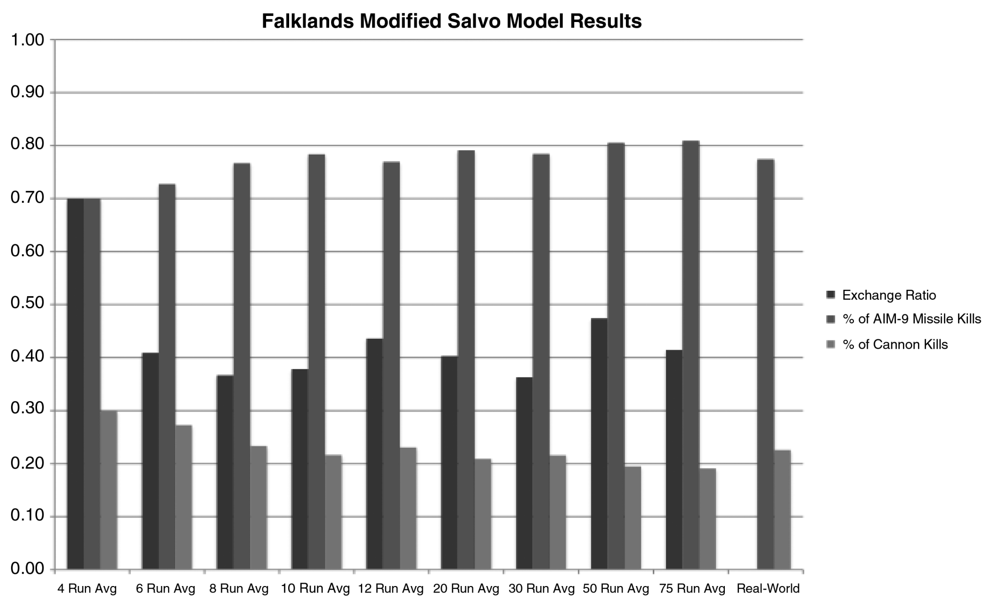

Fig. 6 Falklands modified salvo model Monte Carlo results.

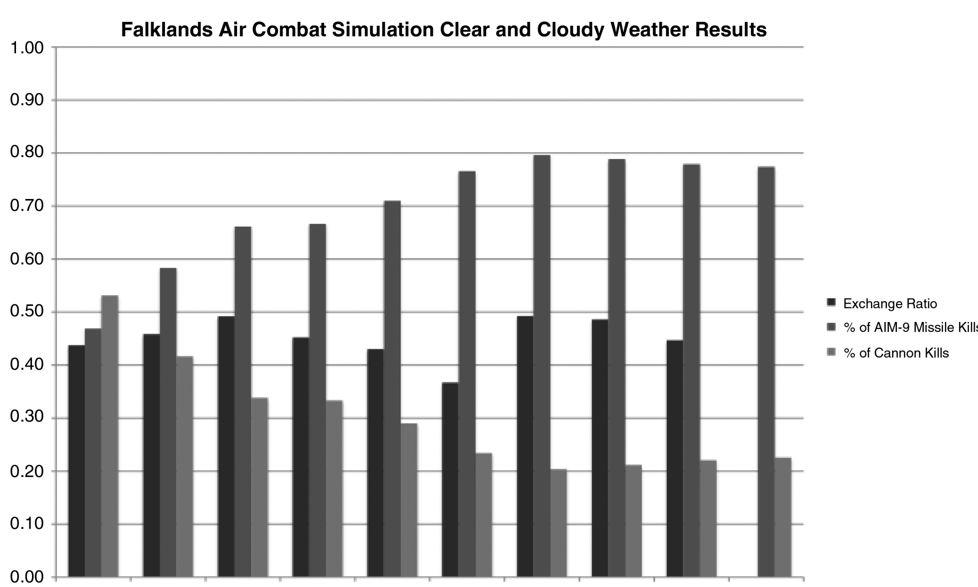

Fig. 7 Falklands air combat simulation Monte Carlo results.

Table 8 Predicted exchange ratios with and without red RF-missile kills

Data source	Exchange ratio
Real-world data	0.00
Monte Carlo modified salvo model with red RF-missile kills	0.58
Monte Carlo modified salvo model without red RF-missile kills	0.37
Monte Carlo air combat simulation with red RF-missile kills	0.45
Monte Carlo air combat simulation without red RF-missile kills	0.38

Table 9 Persian Gulf deterministic modified salvo model results without air controllers

Analysis metric	Deterministic model prediction	Real-world data
Exchange ratio	0.50	0.00
AIM-7M missile kill ratio	0.67	0.62
AIM-9M missile kill ratio	0.33	0.33
Cannon kill ratio	0.00	0.05

Table 10 Persian Gulf deterministic modified salvo model results with air controllers

Analysis metric	Deterministic model prediction	Real-world data
Exchange ratio	0.17	0.00
AIM-7M missile kill ratio	0.67	0.62
AIM-9M missile kill ratio	0.33	0.33
Cannon kill ratio	0.00	0.05

Turning to the Monte Carlo modified salvo model, we observe that the predicted exchange ratio increases above the value actually observed in the Falklands. As the number of Monte Carlo runs increases, the percentage of missile versus gun kills converges towards values observed in the South Atlantic campaign. Figure 6 illustrates the modified salvo model Monte Carlo results.

For the Falklands scenario, the air combat simulation includes a combination of clear and cloudy weather conditions to mimic conditions seen in the South Atlantic. In the simulation, cloudy weather serves to reduce the effectiveness of IR-guided missiles compared with clear conditions. An examination of the air combat simulation results indicates similar trends to the modified salvo model. As illustrated in Fig. 7, the air combat simulation predicts higher than observed exchange ratios, but provides missile/cannon kill percentages that are very close to real-world results. The 75 Monte Carlo modeling and simulation results predict slightly higher AIM-9L kill percentages compared with the observed campaign values.

One potential reason for the observed errors in the exchange ratio predictions for the Monte Carlo runs may involve pilot training. As listed in the assumptions of Sec. III, our models and simulations do not account for differences in pilot training or combat experience. During the Falklands conflict, an example of pilot training affected aerial engagements relates to the Argentinean lack of experience with the French Matra R.530 radar-guided missile. Argentinean pilots' training on the missile system was incomplete before the outbreak of hostilities. Therefore, the pilots were unable to use the R.530 effectively. In the one instance where an Argentinean Mirage launched a R.530 in a head-on engagement with a British Harrier, the Mirage was shot down by the Harrier's all-aspect AIM-9L [6].

We can examine this aspect of pilot training in our Monte Carlo results. Table 8 compares the predicted exchange ratios for 75 replication Monte Carlo sets with and without the inclusion of Argentinean R.530 missile kills. We observe that removing the R.530 missile kills from the study results, reflecting the incomplete Argentinean pilot training, reduces the predicted exchange rate.

VIII. Persian Gulf Scenario Results

Our focus will now shift to the 1991 Persian Gulf scenario. Of the Iraqi aircraft downed in aerial engagements, RF-guided missiles were responsible for the majority of kills, followed by IR-guided missiles and cannon fire [5]. Specifically, radar-guided missiles accounted for 24 confirmed kills, heat-seeking missiles had 13 confirmed kills, while cannon fire shot down 2 aircraft [7]. A first look at the deterministic modified salvo model indicates predicted outcomes compared with real-world results, as outlined in Table 9.

While our deterministic model provides a reasonable prediction of missile kill percentages, the predicted exchange ratio differs greatly from the real-world outcome. One reason our predictions may be erroneous is that we do not model the overwhelming Allied superiority in command and control (C2) during the air battle. Adjusting the deterministic modified salvo model by increasing the number of accurate blue missiles launched in a salvo to account for Allied air controllers results in predicted metrics as illustrated in

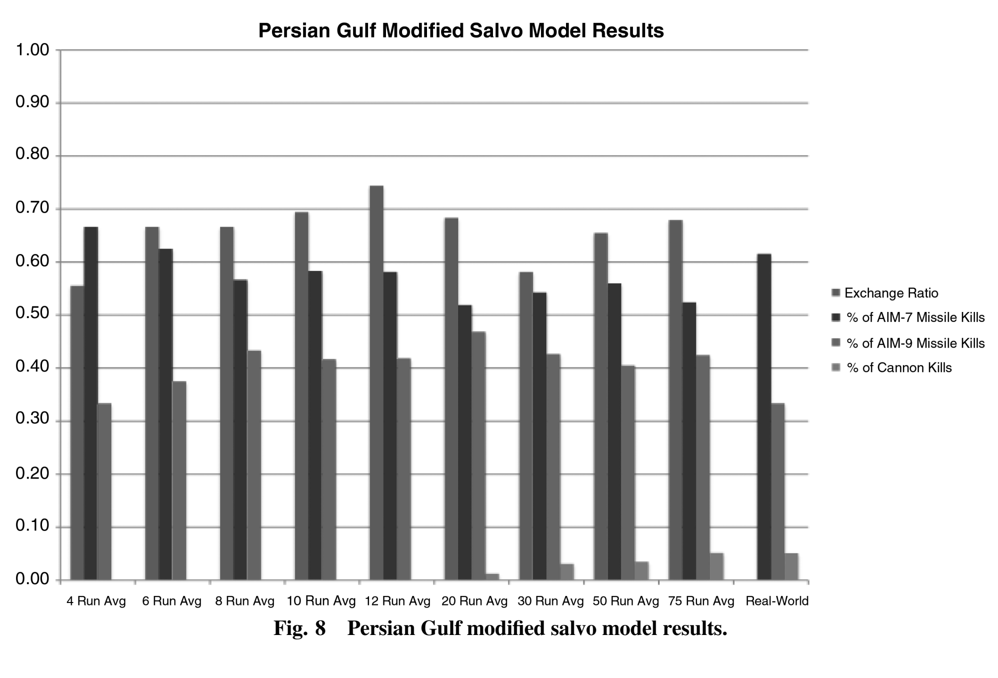

Fig. 8 Persian Gulf modified salvo model results.

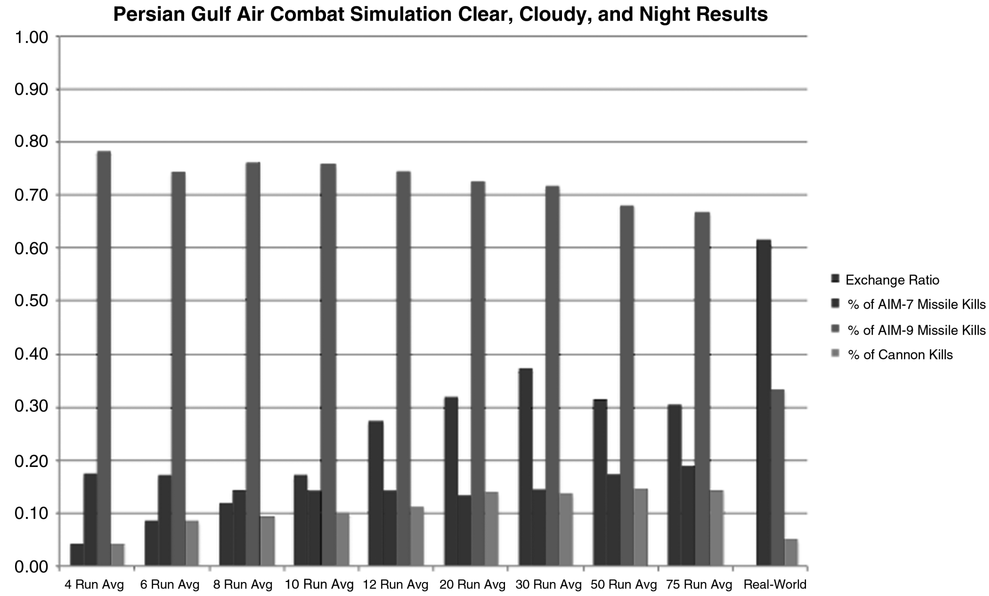

Fig. 9 Persian Gulf air combat simulation results.

Table 10. The updated model predicts the same missile kill ratios as before, but has an exchange ratio closer to that actually observed in 1991.

Including Monte Carlo replications to the modified salvo model provides results as illustrated in Fig. 8. The model predicts an exchange ratio that is too high compared with real-world results, however, it does make reasonable predictions of missile and cannon kill percentages.

Persian Gulf scenario results from the air combat simulation are provided in Fig. 9. As an expansion to our previous inclusion of weather effects and night missions are included in the air combat simulation results. The simulation predicts higher exchange ratios than observed in 1991. The Monte Carlo runs also indicate a stronger reliance on the fire-and-forget AIM-9M heat-seeking missile than actually occurred during the conflict. During the real-world conflict, many of the aerial engagements took place at a longer range than our simulation predicts and Iraqi aircraft often took no evasive maneuvers. Although the simulation does include air controllers for the blue forces, the random initial starting positions and red evasive maneuvers in the simulation may drive shorter-range dogfights than seen during Persian Gulf aerial engagements.

IX. Hypothetical Future Scenario

Finally, let us examine a hypothetical scenario pitting four F-22 Raptors against six Su-27 Flankers. Even though there are no available real-world comparison data for this scenario, the modeling and simulation may still provide useful insights.

Metrics from the deterministic and Monte Carlo modeling and simulation predictions are summarized in Table 11. Exchange ratios varied between 0.17 and 0.78, but in all cases predicted an advantage for the F-22, despite being outnumbered six to four. Our results also indicate a continued reliance on missiles for the majority of successful engagements, but the Monte Carlo runs have cannon kills accounting for between 4 and 10% of the total.

Each of the models predicts that the blue forces should be able to achieve a favorable exchange ratio, even in the face of superior numbers of threat aircraft. Monte Carlo results for the modified salvo model indicate that on average, for each blue aircraft lost, approximately 1.3 red aircraft would be destroyed. The deterministic salvo model and air combat simulation both predict a more favorable exchange ratio of approximately one blue aircraft lost for each 4.8 to 5.9 red aircraft destroyed.

Review of air combat simulation study runs indicates that in many replications the F-22 Raptor is able to detect and engage the red aircraft first. This provides blue an advantage reflected by the predicted 0.20 exchange ratio, despite being outnumbered in the hypothetical scenario. With the exception of the South East Asia scenario, the Monte Carlo models and simulations also predict higher exchange ratios compared with historical results. If applied to the hypothetical scenario, the exchange ratio of blue to red aircraft may be better than predicted by the simulations.

In addition to the exchange ratio, the models provide metrics for missile and cannon kill percentages. All three models and simulations predict that 90 to 100% of the red losses are due to missiles. The active seeker of the AIM-120 coupled with a longer

Table 11 Hypothetical future scenario modeling and simulation comparison results

Data source	Exchange ratio	AIM-120 kills	AIM-9x kills	Cannon kills
Deterministic modified salvo model	0.17	0.50	0.50	0.00
Monte Carlo modified salvo model	0.78	0.42	0.48	0.10
Monte Carlo air combat simulation	0.21	0.59	0.36	0.04

Table 12 South East Asia modeling and simulation comparison results

Data source	Exchange ratio	AIM-7B kills	AIM-9B kills
Real-world data	0.31	0.57	0.38
Deterministic modified salvo model without ROE restrictions	0.00	0.67	0.33
Deterministic modified salvo model with ROE restrictions	0.25	0.75	0.25
Monte Carlo modified salvo model	0.28	0.86	0.13
Monte Carlo air combat simulation	0.85	0.27	0.73

Table 13 Falklands Islands modeling and simulation comparison results

Data source	Exchange ratio	AIM-9l kills	Cannon kills
Real-world data	0.00	0.77	0.23
Deterministic modified salvo model	0.00	0.67	0.33
Monte Carlo modified salvo model with red RF-missile kills	0.41	0.81	0.19
Monte Carlo modified salvo model without red RF-missile kills	0.37	0.81	0.19
Monte Carlo air combat simulation with red RF-missile kills	0.45	0.78	0.22
Monte Carlo air combat simulation without red RF-missile kills	0.38	0.78	0.22

Table 14 Persian Gulf modeling and simulation comparison results

Data source	Exchange ratio	AIM-7m kills	AIM-9m kills	Cannon kills
Real-world data	0.00	0.62	0.33	0.05
Deterministic modified salvo model without air controllers	0.50	0.67	0.33	0.00
Deterministic modified salvo model with air controllers	0.17	0.67	0.33	0.00
Monte Carlo modified salvo model	0.68	0.52	0.42	0.05
Monte Carlo air combat simulation	0.30	0.19	0.67	0.14

range than the AIM-9X provides the F-22 with the ability to reduce the number of short-range dogfights. The modified salvo models predict that 42 to 50% of the kills achieved by the F-22 will be due to the AIM-120 in the hypothetical scenario. The air combat simulation indicates an even higher reliance on the AIM-120, with the active-seeker RF-guided missile responsible for nearly 60% of aircraft kills.

Not all of the predicted kills achieved by the F-22 are the result of missiles. The Monte Carlo modified salvo model indicates that the internal cannon accounts for 10% of aircraft kills. The air combat simulation predicts that 4% of kills will be achieved using the cannon. These results align with predictions that the cannon is still relevant even in engagements between sophisticated, highly maneuverable fighters employing fire-and-forget missiles [5].

X. Conclusions

As a review of our results, we will go back to each of the historical scenarios to see how our modified salvo model and air combat simulation predictions compare to real-world results. The metrics evaluated include exchange ratio, missile kill percentages, and cannon kill percentages. Table 12 illustrates the comparison of South East Asia real-world data to the deterministic and Monte Carlo modeling and simulation predictions based on 75 replications. Results for the Falklands Islands and Persian Gulf campaigns are provided as Table 13 and 14, respectively.

Exchange ratio predictions often differed from real-world results. These differences point to the importance of including appropriate representations of real-world effects in modeling and simulation. We observed that factors such as ROE, pilot experience with missile systems, and the presence of air controllers had important effects on simulation results. Other factors that may have contributed to differences in exchange ratios include overall pilot training, combat experience levels, and the ever-present “fog of war.”

Despite the assumptions listed in Sec. III, modeling and simulation predictions of missile and gun kill ratios were often surprisingly close to real-world results. Although extrapolating campaign-level results from a single type of engagement contributed to higher exchange ratios, predictions for missile and gun kill percentages typically mirrored real-world results. For the South East Asia and Persian Gulf scenarios, two of the three models and simulations predicted at least one missile or gun kill ratio within 0.25 of the actual result. In the Falklands Islands scenario, two of the three models and simulations predicted both AIM-9L and cannon kill ratios within 0.05 of the real-world observations.

As a result of some of the simplifying assumptions, there are a number of potential areas for future enhancements to the models and simulations we employed for this study. These possible enhancements to more closely replicate real-world effects include: 1) inclusion of different sortie types beyond fighter sweeps, 2) examination of different numbers of aircraft (M versus N) involved in engagements beyond the fixed four blue versus six red aircraft, 3) variation in pilot skill levels and/or combat experience, and 4) inclusion of human-in-the-loop study runs.

The results of this comparison indicate that even simple models and simulations can provide useful metrics. Care must be taken, however, to account for sufficient real-world effects. The use of multiple models and/or a number of study runs can also help improve predictive capability. Notably, even where real-world data are unavailable, as in our hypothetical future scenario, the predictions of combined modeling and simulation runs can generate interesting results or highlight areas for further study.

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