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BASIC STUDIES ON ELECTRO-ENGERGETIC PHYSICS (EEP) WEAPONS TECHNOLOGIES

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Final Report

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15. SUBJECT TERMS
Electro-Energetic Weapons, Wargame Simulations, Tipping Points, Risk Assessment.

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Basic Studies on Electro-Energetic Physics (EEP) Weapons Technologies

Final Report

15 Nov 2014

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256-289-9631

Contract FA9550-09-C-0210

Dedicated to the memory of Dr. Robert Barker.

Abstract

Research was conducted into the representation of EEP weaponry and its potential use in future warfare. Physics-based modeling was created for each of the weapon technologies High Power Microwave, High Energy Laser, Charged Particle Beams, and Hypersonic Railguns. Using these representations, wargame simulations of various scale and scope were used to understand the potential impact of these weapons on future warfare and in some cases, how doctrine would need to be changed. Mathematical analysis was further used on the simulation results to derive key aspects of the outcomes. This required advanced mathematical analysis into subjects such as tipping points and risk assessment. The research conducted as part of this effort provides insight and potential benefit into the future use of advanced weaponry and how wargame representations of such weaponry provides valuable understanding based on current understanding of weapon development. And the analysis techniques created under this project can be used to better understand different dynamic situations and evaluate various options.

1.0 Introduction

The research associated with this effort produced several significant results:

- Physics-based modeling of advanced weaponry including HPM (High Power Microwaves), HEL (High Energy Lasers), Hypersonic Railguns, and Charged Particle Beams that are suitable for inclusion in wargame simulations (Section 2).
- Advanced wargame simulations supporting research into advanced weaponry and doctrine in a number of different scales and scopes ranging from ground to naval and air warfare settings (Section 3).
- Analysis of the relative benefit of advanced weaponry on future warfare as well as understanding limitations of such weaponry (Section 4).
- Detailed results associated with a possible future implementation of HPM on UAVs (Unmanned Aerial Vehicles) resulting in an understanding of enemy countermeasures and future doctrine (Section 5).
- New mathematical analysis into the topics of Tipping Points and Risk Assessment that provide crucial insight into the outcomes of warfare scenarios and the use of advanced weaponry (Sections 6 and 7).
- Initial investigations into the behavioral and other non-attritional effects of advanced weaponry (Sections 8, 9, 12, and 13).
- Multiple interactions with other researchers and contributions to other efforts (Sections 10 and 11).
- Significant transitions to both PME (Professional Military Education) as well as numerous commercial transitions (See reference sections).

In addition to these accomplishments, this research provides a basis for continued investigations into the possible benefit of advanced weaponry research and furthermore begins an important investigation into behavioral and other non-attritional effects of advanced weaponry.

2.0 Weapon Technologies

This section establishes physics-based representation of four important advanced weapons: High Power Microwaves, High Energy Lasers, Hypersonic Railguns, and Charged Particle Beams. Each of these is modeled in such a way as to make these representations suitable for inclusion in wargame simulations and thus by doing so provides a basis for analysis into the possible benefits as well as limitations of such weaponry. It is critical to appreciate that each representation given here is very much based in an energy and power analysis which establishes the model in a real-world setting and thus avoids speculation into results that are not actually physically possible.

2.1 High Power Microwaves

The fundamental basis for the effect of HPM (High Power Microwaves) is based on the concept of electrical field, measured in volts per meter (V/m) as described in the John Tiller Software technical report [T1]. As such, given a power output of W watts over a projected area of A m^2, the resulting electrical field E is given by:

$$E=\sqrt{\frac{2W}{Ace}}$$

For example, given a 10 GHz 1 GW HPM with a 40 dBi antenna, then at 8 nm we will get an electrical field of about 1 kV/m [see T1] which is taken to be the basis for RF Upset in electrical effects modeling.

Likewise, in the John Tiller Software technical report [T5], an investigation is made into the possibility of an airborne version of the ADS (Active Denial System). This starts with the published specifications for the existing ADS:

- Power = 100 kW
- Frequency = 95 GHz (IEEE W Band)
- Antenna size = 86 in (218 cm)
- Effective range = 750 m
- Beam size at 750 m = “full body”

Based on these specifications, it is possible to derive the following:

- Antenna gain = 63.75 dBi (at 0.5 aperture efficiency)
- Beam diameter at 750m = 1.3 m (4 ft 3 in)
- Field strength at 750 m = 5 kV/m
- Power density at 750 m = 3.3 W/cm^2

We then take 5 kV/m as the basis for the dielectric heating effects of the ADS and the resulting human deterrence. To next consider an airborne version of the ADS, we increase the power output to 10 MW and assume a 4 second discharge.

To establish the energy basis for this output, we consider the GE TF-34 turbine engines used on the existing A-10. The hypothesis is that an unmanned version of the A-10 is developed where the existing 30mm GAU-8/A Avenger cannon is removed and replaced with a 10 MW HPM powered by a 40 MJ capacitor. Using published specifications of this engine, we derive:

- 9,275 lbf thrust
- 0.37 lb / (h * lbf) Specific Fuel Consumption (SFC)

Using 40 MJ/kg as the specific energy of jet fuel, the total fuel power burned equals:

9275 * 0.37 / 2.2 * 40 / 3600 = 17 MWth per engine

At 31% thermal efficiency, each engine produces 5.27 MW of output power. We will assume that for the A-10 that 60% power is required for cruise flight (based on a cruise speed of 300 kts vs. maximum speed of 381 kts) and thus 40% of engine power is available in cruise. This provides electrical power in cruise of:

5.27 * 0.4 = 2 MWe per engine, 4 MWe total

Thus a 40 MJ capacitor can be charged in 10 seconds. Discharging the capacitor at 10 MW for 4 seconds, we assume that this is then used to power a 5 MW 95 GHz microwave transmitter at 50% efficiency.

This results in the following design configuration for our airborne ADS:

- 5 kV/m field strength at 750 m
- Antenna gain = 47 dBi (at 0.7 aperture efficiency)
- Antenna size = 27 cm (10.6 in)
- Beam diameter at 750 m = 10.8 m (35 ft)

This implementation could then generate ADS effects at 750 m using a small antenna over a 35 ft diameter area in what is called in the report [T5] an EQ-10. This implementation would provide a Non-Lethal Close Air Support (NLCAS) capability that could be used in combat situations against both military and irregular forces as well as situations potentially involving collateral damage.

2.2 High Energy Lasers

The wargame modeling of HEL (High Energy Lasers) is derived in the John Tiller Software technical report [T2]. The fundamental calibration for laser effects there is based on projected energy per area measured in Joules per square centimeter. Based on analysis given in the book *Effects of Directed Energy Weapons* by Nielsen, it is possible to base laser effects on the following guidelines shown below in Table 2.1.

Effect	Intensity
Vaporize	10 kJ/cm^2
Melt	3 kJ/cm^2
Soften	1 kJ/cm^2

Table 2.1. Summary of laser effect calibrations.

Having established these values, it is then possible to investigate the effect of various laser systems. For example, given an airborne laser with the following specifications:

- 100 kW power
- 1.315 µm wavelength
- 0.22 m diameter beam

it is possible to derive based on the following calculations [see T2], the Beam Radius w_0

$$w_0 = \frac{D}{3\sqrt{2}}$$

and Power Density S_R at the Rayleigh Range of the laser:

$$S_R = \frac{P}{\pi w_0^2}$$

which in the case described results in a 1.1 kW/cm^2 power density. Thus a 3 second firing of such a weapon would result in melting of the target at the point the laser beam was aimed.

2.3 Hypersonic Railguns

In the John Tiller Software technical report [T3], the wargame modeling of hypersonic weapons and railguns in particular is established. The basic calibration in that case is based on the fundamental equation of kinetic energy

$$E = \frac{m v^2}{2}$$

For example, given a 3 kg projectile traveling at 3,000 m/s, the kinetic energy would be 13.5 MJ. It is then possible to establish the specifications for a 32 MJ railgun along these lines.:

- Projectile mass = 15 kg
- Projectile length = 30 in (76 cm)
- Barrel length = 10 m
- Muzzle velocity = 2,100 m/s

To understand how such an advanced weapon compares with conventional weaponry, it is illustrating to compare these figures with the M-1 Abrams M256 120mm gun firing a M829A1 kinetic energy round

- Muzzle velocity = 1,575 m/s
- Projectile mass = 9.0 kg
- Computed kinetic energy = 11.2 MJ

Note however, that the round of the M-1 tank is discarding sabot and so the effectiveness (see [T3]) is given by:

- Density of depleted uranium = 0.01910 kg/cm^3
- Penetrator mass = 4.6 kg
- Penetrator ratio of length to diameter = 35
- Penetrator energy = 5.7 MJ

and so only about half the energy of the round itself.

To compute the penetration of kinetic energy penetrators, we use the DeMarre equation:

$$E = C \cdot D^{1.5} \cdot d^{1.4}$$

where *E* is the kinetic energy of the round, *C* is the penetration coefficient, *D* is the diameter of the round, and *d* is the penetration distance. Based on the calibration of the penetration coefficient of 0.0052 derived in [T3], we can project the penetration of a 64 MJ railgun round in concrete (using a density of 2.4 g/cm^3 as compared with steel with a density of 4.85 g/cm^3) as:

- Length = 76 cm (given), diameter = 3.7 cm (computed), giving an aspect ratio of 20:1.
- Estimated penetration of projectile in concrete = 700 cm.

2.4 Charged Particle Beams

A related but more technologically advanced type of kinetic energy weapon is that of a CPB (Charged Particle Beam). As described in technical report [T4], these can be described for the purposes of wargame simulation using these typical characteristics as described in the book *Effects of Directed Energy Weapons* by Nielson:

- 1 GeV (Giga electron Volt) protons
- Particle speed v of 0.866 c (c = the speed of light 3 x 10^8 m/s)
- I = 30 kA current
- w = 1 cm radius beam

There are multiple factors that affect the range limitation of such a beam in the atmosphere which in general depend on the density of the atmosphere and thus are greatest at sea level:

- Evolution of Beam Radius. At I = 30 kA and K = 1 GeV, we assume an maximum effective beam range at sea level to be about 8 km based on beam radius evolution.
- Ionization of the Atmosphere. We assume an energy loss due to ionization of 7 x 10^5 eV/m

at sea level (page 298). This is equal to 0.7 GeV/km. Thus a 1 GeV beam would lose all energy from ionization after 1.5 km.

- Braking Radiation (Bremsstrahlung). We assume that for protons, this does not produce a significant effect.
- Nuclear Interaction. We assume that a sea level, nuclear interaction of the protons with the atmosphere limits the effective beam to 1.45 km.

These effects are all dependent on the density of the atmosphere and so the ranges here would all be 10 times as long for example if the density of the atmosphere was 1/10 that of sea level. However, at sea level by default this would limit the range of the weapon to be under 1.5 km.

In Nielsen's book, he describes a technique of Hole-Boring used with the weapon (see [T4]). In this approach, the particle beam is used to heat the atmosphere and thus cause its density to decrease. Once this occurs, the effective range of the beam is increased in the portion of the atmosphere heated by the beam. The beam is thus fired again at a longer range to heat another portion of the atmosphere, thereby increasing its range again. We assume these values:

- Heating time = 0.3 μ sec.
- Expansion time = 30 μ sec.
- Density reduction = 1/10.

This then extends the effective range of such a weapon out to 15 km.

3.0 Wargame Simulations

In the course of John Tiller Software research, advanced wargame simulation technology has been implemented which supports comprehensive analysis of warfare scenarios at varying scale and scope.

The figure below shows screenshots of these 6 simulation engines. They range from the tactical *Squad Battles* engine up to the more strategic or grand-operational *Strategic War* engine and also include the airpower-centric *Modern Air Power* engine and the naval-centric *Naval Campaigns* engine.

The advantage of having such a wide range of simulation engines available means that any particular research question can be addressed using a simulation engine that is particularly suited for the scope and scale of the problem. For example, research into nano UAVs is effectively addressed by *Squad Battles*, while the operational impact of UCAVs on air superiority is effectively addressed by *Modern Air Power*.

Figure 3.1. Screenshots of the 6 simulation engines used in research by John Tiller Software.

3.1 Squad Battles

The John Tiller Software wargame simulation *Squad Battles* is particularly suited for simulation analysis at the tactical level. It can be used for detailed analysis of small unit tactics in situations such as Close Air Support (CAS). As such, it can be used to model and simulate advanced weaponry such as the Active Denial System and its effects. Figure 3.2 below shows a typical screenshot from this simulation engine.

Figure 3.2. Screenshot from *Squad Battles: Modern War*

The game system is particularly flexible and has been successfully implemented in a number of commercial game releases (see [CT2] and [CT4]) including:

- *Vietnam* – Army and Marine ground actions from the Vietnam War.
- *Tour of Duty* – Focuses on air mobility actions from the Vietnam War.
- *The Proud and the Few* – Marine combat in the Pacific during World War II.
- *Eagles Strike* – American combat in Europe from D-Day to the end of World War II.
- *The Korean War* – Ground actions of the Korean War.
- *Advance of the Reich* – Combat between Germany and the Soviet Union in World War II from 1941 through 1942.
- *Pacific War* – Army and multinational combat in the Pacific during World War II.
- *Soviet-Afghan War* – War in Afghanistan in the 1980's.
- *Winter War* – War between Finland and the Soviet-Union during World War II.
- *Modern War* – Covers the modern war in Iraq and Afghanistan.
- *Falklands* – Conflict in the Falkland Islands between Great Britain and Argentina in 1982.

The game system is turn-based, with map grids consisting of 40 meter hexes, and turns representing 10 minutes of real-time.

The Squad Battles game engine supports the following game design features:

- Individual squads, crews, and other small units of infantry and ground forces.
- Individual leaders in a hierarchical command structure.
- Ratings and metrics of leadership, effectiveness, fatigue, and morale.
- Specialized weaponry appropriate to the time period and setting.
- Weapon ratings for range, lethality, penetration, and reliability.
- Specialized features such as shaped charges, indirect fire, smoke rounds, surface-to-air missiles, and other unique characteristics.
- Representations of national characteristics and specialized tactics such as suicide attacks and suicide weapons (The Japanese banzai charge and the Russian human wave attacks of World War II being two good examples).

Squad Battles: Modern War is a development in the Squad Battles game system covering modern tactical combat. Its scale is particularly good for representing modern small unit tactics and in particular, those corresponding to asymmetric combat.

The advantages of investigating *Squad Battles* scenarios include:

- Detailed dynamics of both military small unit tactics can be considered.
- Likewise, detailed dynamics of paramilitary and non-combatant participants in tactical

situations can be investigated.

- Detailed representations of advanced weaponry such as the Active Denial System can be simulated.
- Results from *Squad Battles* scenarios can be used to justify higher-level effects represented in the other simulation engines.

3.2 Armor Battles

The *Armor Battles* simulation engine is the next step up from *Squad Battles*. In *Armor Battles* hexes are 400 meters while turns are 1 hour long. The engine is designed to represent ranged fire engagements particularly involving armored forces. It is being implemented in historical situations post World War II. The screenshot below shows an implementation addressing potential future warfare in Korea and in particular shows a meeting engagement of armored forces south of Pyongyang.

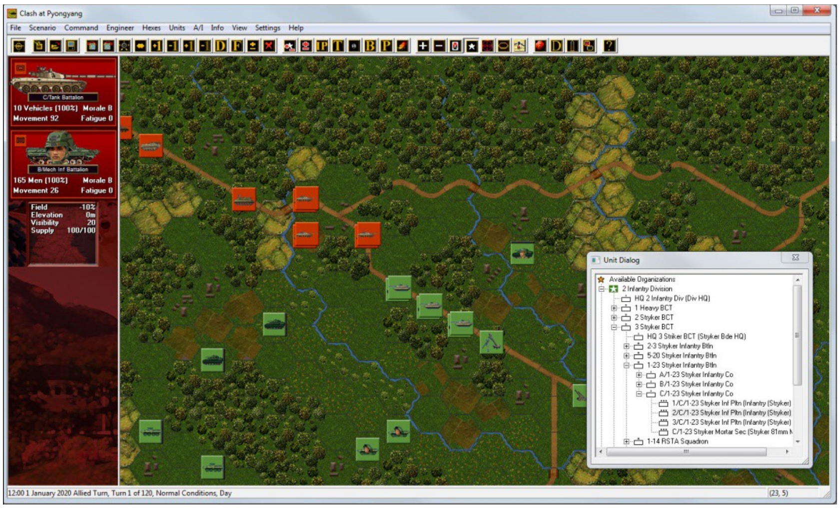


Figure 3.3. Screenshot from *Armor Battles: Battles of Korea*

This game engine has also been the basis for commercial development (see [CT6]).

3.3 Modern Campaigns

Modern Campaigns is an operational representation of ground combat. The game system has been implemented in the following commercial releases:

- *Fulda Gap '85* – Hypothetical campaign covering Warsaw Pact attack against NATO forces in central Germany in 1985.
- *Middle East '67* – Covers the wars in the Mideast between Israel and Arab countries from 1967 through 1975.
- *Korea '85* – Hypothetical attack by North Korean forces against South Korea and coalition forces in 1985.
- *North German Plain '85* – Extends the scope of *Fulda Gap '85* to cover northern Germany.
- *Danube Front '85* – Completes the World War II trilogy with Fulda Gap and North German Plan.

In addition, a military professional version of Modern Campaigns has been developed with the flexibility to address any situation or setting. In Figure 3.4, a screen shot showing a scenario from the historical Desert Storm war in Iraq is shown.

Figure 3.4. Example from *Modern Campaigns* showing Desert Storm situation at Basrah.

Modern Campaigns is turn based with each turn typically representing 2 hours of real-time and hexes measuring 1 mile across.

The *Modern Campaigns* game engine supports a number of features that make it particularly suitable for representing modern ground operations:

- Units consist of company and battalion-sized units for the most part and can represent infantry, armor, and artillery as well as helicopter and airplane units.
- Headquarter units and other issues of communication and SIGINT allow a detailed representation of modern C2 issues.
- Supply and other logistical issues as well as human factors such as morale and fatigue are represented.
- Specialized weaponry such as thermal imaging is supported by the game engine as well as guided missiles, chemical weapons, and artillery mines.
- Asymmetric aspects of modern warfare including deception units and partisans are provided.

The game engine has also been the basis for several commercial releases (see [CT1], [CT3], [CT5], [CT8] and [CT9]).

3.4 Strategic War

Strategic War is a campaign-level turn-based simulation which is very flexible with respect to scale and scope. It has been used for many years by John Tiller Software not only for Air Force research but also for a number commercial releases. A screenshot from *Strategic War* is shown below in Figure 3.5.

The flexible scale and scope of the *Strategic War* simulation engine supports a number of implementations including:

- *War in Europe* – A series of 5 releases covering World War II in Europe. Typical units are battalion, hexes are 10 kilometers, and turns are 2 days.
- *War in Vietnam* – The historical war in Vietnam 1965-1975. Typical units are battalion, hexes are 5 kilometers, and turns are 1 day.
- *War in Korea* – The historical war in Korea 1950-1953. Typical units are battalion, hexes are 5 kilometers, and turns are 1 day.
- *War in the Sinai* – A demonstration release covering the Israeli-Egyptian battles in the Sinai. Typical units are battalion, hexes are 10 kilometers, and turns are 1 day.
- *War in the Pacific* – Looks at possible future war in the Pacific. Typical units are brigades, hexes are 30 kilometers, and turns are 3 days.

Figure 3.5. Screenshot from *Strategic War*.

The advantages of *Strategic War* include:

- Campaign-level scenarios can be investigated which incorporate both the tactical-level effects of *Squad Battles* as well as the mission-level effects of *Modern Air Power*.
- *Strategic War* can be used to fully investigate issues of joint warfare involving land, sea, and air components.
- The turn-based nature of *Strategic War* provides the basis for considering campaigns of any length in a reasonable amount of simulation time.
- The longer time scale of a campaign-level model can capture the accumulation of second order effects of the use of various classes of weaponry.

3.5 Modern Air Power

Modern Air Power is a mission-level real-time simulation of modern air warfare. It has been used for many years in both Air Force research such as this project as well as an education tool in the Squadron Officer College at Maxwell AFB. A screenshot from *Modern Air Power* is shown below in Figure 3.6.

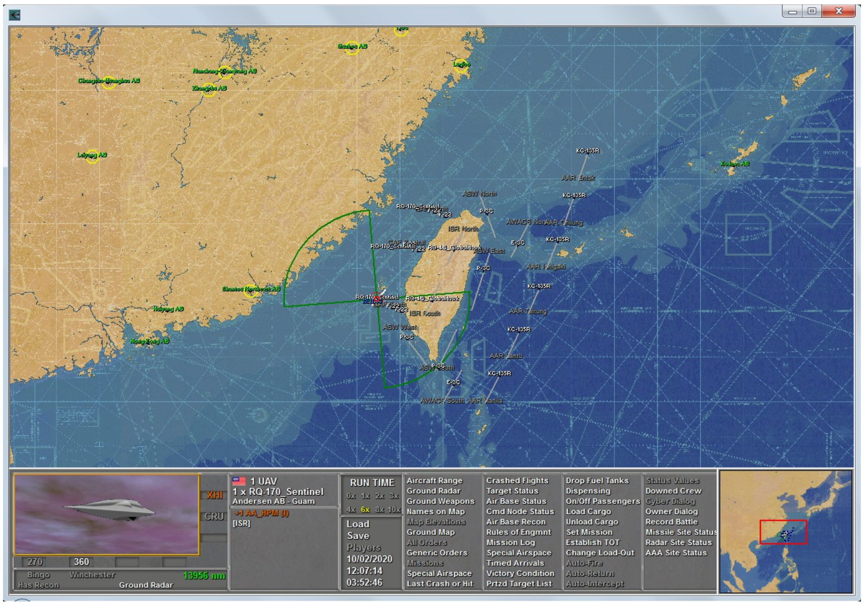


Figure 3.6. Screenshot of *Modern Air Power* showing HPM-equipped UAV.

Modern Air Power includes the following features:

- Real-Time. Runs from 1x to 10x real-time and is network-capable.
- Mission Level. Covers air operations at the mission level and includes such scenarios as the Vietnam War and future hypothetical conflict.
- Full-range of modern ordnance including IR, Semi-Active, and Active Radar air-to-air missiles, anti-radiation and other types of air-to-ground missiles, surface-to-air missiles, AAA, cluster bombs, rockets, napalm, and both precision and non-precision general purpose bombs.
- Scenario editor offers numerous weapon load options for different aircraft.
- Complete "Fog of War" spotting including radar acquisition, stealth effects, ability to dispense chaff corridors, and altitude radar effects, as well as visibility effects.
- Includes specialized features such as external fuel tanks, ECM pods, and chaff pods.
- Includes jamming aircraft and jamming effects. Also models airborne radar such as AWACS and JSTARS.
- Incorporates a Battle-Damage-Assessment (BDA) recon feature.
- Includes both mid-air refueling from tankers as well as on-ground in-base refueling.
- A complete database of modern aircraft and ordnance from the Vietnam War to present day has been developed and includes all significant prop, jet, and helicopter aircraft as well as

satellites.

- Use can program routing for aircraft to fly or tracks/orbits
- Has selectable options to display or hide sensor coverage fans and weapon range envelopes
- Features options for playing background communications radio audio and system sounds.
- Incorporates a Search-and-Rescue feature based on combat losses during the scenario.
- Has a record/playback feature which allows air battles to be recorded to a file and then played back at a latter time. Users can stop the replay at any time and deviate from the recording.
- Incorporates a Cyber Warfare feature enabling interactive, automated, and network-enabled simulations of cyber warfare in the context of a kinetic air campaign.

The advantages of utilizing *Modern Air Power* include:

- Detailed scenarios representing mission-level air power situations can be investigated.
- Lower-level results from *Squad Battles* can be abstracted in *Modern Air Power* in cases such as Close Air Support.
- *Modern Air Power* has support for all modern day conventional aircraft and weaponry as well as advanced weaponry such as HPM and HEL.

The game engine has been used in multiple commercial releases (see [CT7]).

3.6 Naval Campaigns

The *Naval Campaigns* wargame engine is a real-time implementation of naval operations that has been implemented in a number of commercial wargames by John Tiller Software:

- *Jutland* – The historical naval battle of World War I between the British and German fleets.
- *Tsushima* – The historical naval battle of the Russo-Japanese War.
- *Guadalcanal* – Covers the naval battles associated with the Guadalcanal campaign of World War II in the Pacific.
- *Midway* – Includes both the naval battle of Midway as well as other major carrier battles in the Pacific of World War II.

Naval Campaigns supports simulation of modern tactical naval situations, particularly those involving situations such as the Persian Gulf. Figure 3.7 below shows a typical *Naval Campaigns* scenario.

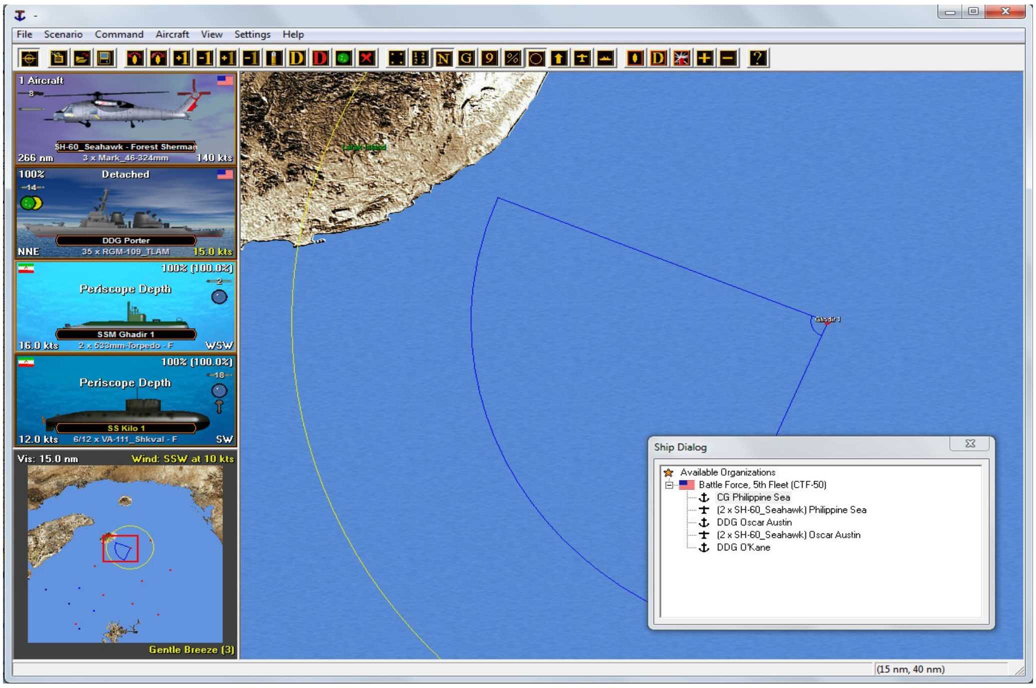


Figure 3.7. *Naval Campaigns* scenario in the Persian Gulf.

4.0 Simulation Results

In this section, each of the weapon systems modeling in Section 2 is applied to one of the wargame simulations described in Section 3. A detailed investigation of HPM in *Modern Air Power* occurs later in Section 5. In each case given here, scenarios were used to generate aggregate outcomes which provide insight into the possible benefit of such weaponry. It is important to realize that in some cases, because of energy and power limitations or some other limiting factor, appreciable benefits were not demonstrated. Obviously it is crucial to understand such limitations in the pursuit of research into advanced weapons.

4.1 Active Denial System (ADS) in Squad Battles

Research looked at the effects of advanced weaponry in *Squad Battles* in the case of the Active Denial System (ADS). An implementation of ADS was used in a *Squad Battles* scenario of the historical defense of the base at Wanat in Afghanistan. Interestingly enough, the results of this analysis, shown below in Figure 4.1, were inconclusive.

In this figure two outcome histograms are displayed, one in red (ADS) and another in blue (conventional). The two histograms basically have no difference. As it turns out, the current implementation of the ADS uses a very large high-gain antenna which becomes an easy target for enemy RPG (Rocket Propelled Grenades). It was found in this investigation that the ADS is lost early in the scenario and thus does not provide any meaningful contribution to the defense of the base. One interesting question future research might address is whether an airborne implementation of ADS would indeed show a benefit.

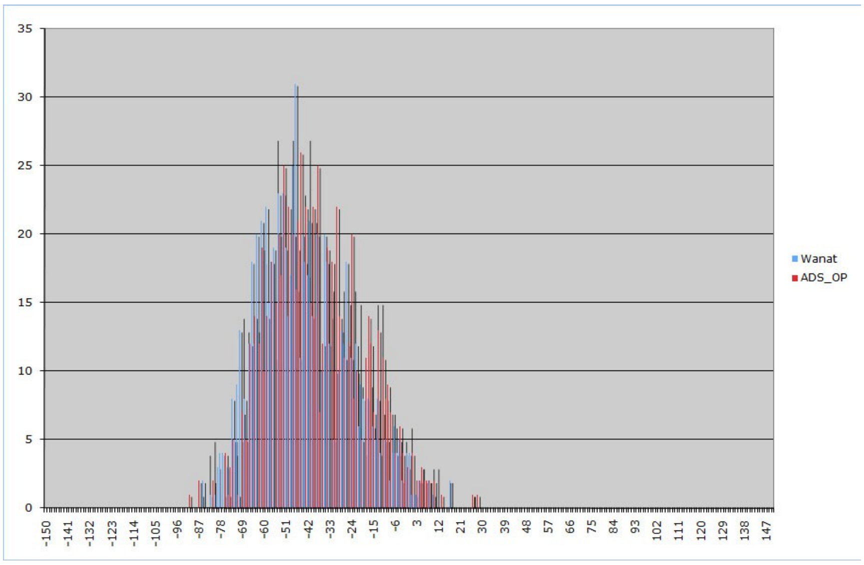


Figure 4.1. Comparison of ADS-equipped base defense with conventional in *Squad Battles.*

4.1 Railguns in Armor Battles

Suppose it was required to equip a tank with a railgun based on the following specifications:

- Railgun requires no more than 50% of engine power so that the tank can maneuver while firing.
- There is enough excess engine power to fire the railgun every 10 seconds.

The M-1 Abram tank uses a 1.12 MW Honeywell AGT1500 turbine engine. If we have 0.5 MW available for charging the railgun and have 10 seconds to do so, then we get a total 5 MJ of output energy from the engine. Assuming 50% railgun efficiency, then the railgun will only have 2.5 MJ of energy, comparable to the Blitzer railgun but only half of the kinetic energy of the standard armor piercing penetrator currently used with the M-1.

It would thus take a 1.5 MW engine to produce energy equal to the standard penetrator. Likewise, with a 3 MW engine, we would have 2.5 MW available for charging, giving 25 MJ in 10 seconds, resulting in a 12.5 MJ railgun round, or approximately twice the energy of a standard discarding sabot penetrator.

The scenario used to generate the comparison is a hypothetical armor meeting engagement in a future conflict. We will compare two versions of this scenario: one where the M1 tank is equipped with the standard 120mm cannon and one where the M1 tank (with increased engine power) is equipped with a 12.5 MJ railgun. We model this in *Armor Battles* as two types of tanks, one with a Hard Attack Factor of 32 and the other with a HAF of 52. We also discount the Soft Attack Factor of the M1 tank from 24 to 12 to account for the lack of high explosive rounds in the railgun version.

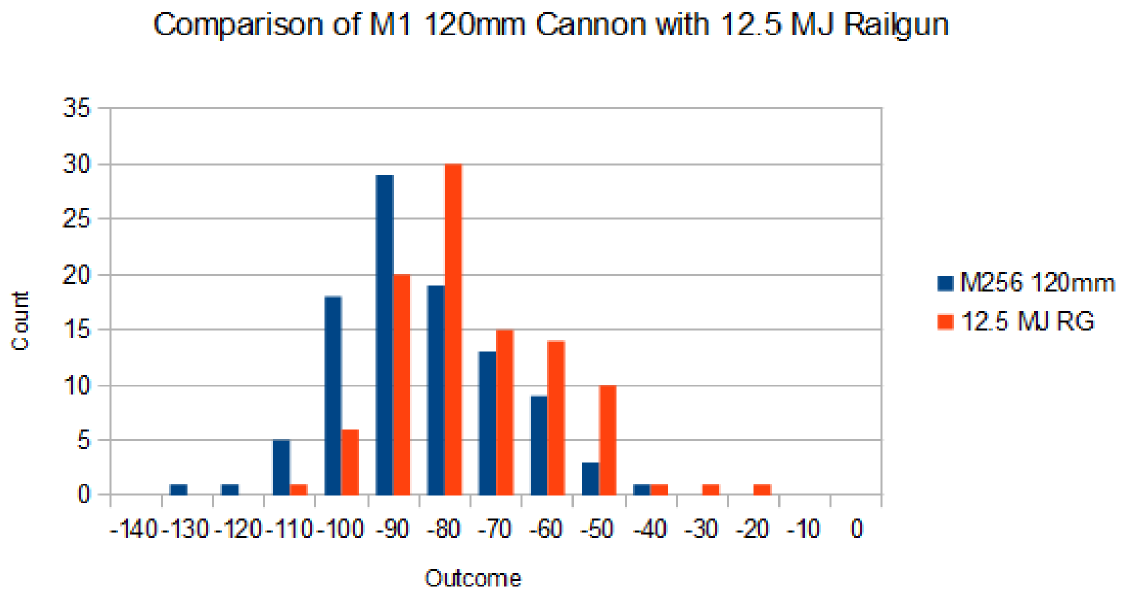


Figure 4.2. Histograms showing comparison of conventional 120mm results with railgun.

To generate the simulation results, each scenario is run in batch multiple times and the final victory point outcome of each run is captured. The point values are then collected in the form of a histogram where outcomes to the left represent outcomes less favorable to the blue side while outcomes to the right represent outcomes more favorable to the blue side. Thus, any shift of the outcome histogram to the left is negative while shifts to the right are positive with respect to the blue side. Figure 4.2 above shows the two histogram results obtained from these simulation runs.

Since the histogram associated with the railgun weapon shows a shift to the right, this demonstrates that there is a positive influence to the outcome of this scenario as a result of replacing the standard 120mm cannon with the railgun. However, the shift is marginal and fails to demonstrate a significant outcome change.

4.2 Charged Particle Beams in Modern Campaigns

The analysis that is done in this section is based on a comparison with a baseline scenario in *Modern Campaigns*. A screenshot of that scenario is shown below in Figure 4.3. The baseline scenario uses conventional Marine forces and equipment and is based on the situation of a Marine attack on enemy forces following an amphibious invasion. The Marine assets include the M-1 tank and the Sea Cobra and Super Cobra attack helicopters.

Figure 4.3. Screenshot from baseline scenario in *Modern Campaigns.*

In the comparison scenario, the Sea Cobras and Super Cobras were replaced with Cobras equipped with the 48 MJ CPB weapon. Each scenario was run 400 times and the outcomes of each scenario, as measured by a victory point calculation which includes both attritional and objective results, were graphed in a histogram that compares the two. These results are shown below in Figure 4.4.

In this figure, the number of outcomes in each bin is shown where the bins are based on victory point outcomes. Higher victory point outcomes are better for the blue side while lower victory point outcomes are better for the red side. Thus a shift of the histogram to the right is better for blue and vice versa. Figure 4.4 shows a significant increase in the outcome just based on changing the 4 flights of Cobras in two Regimental Landing Teams.

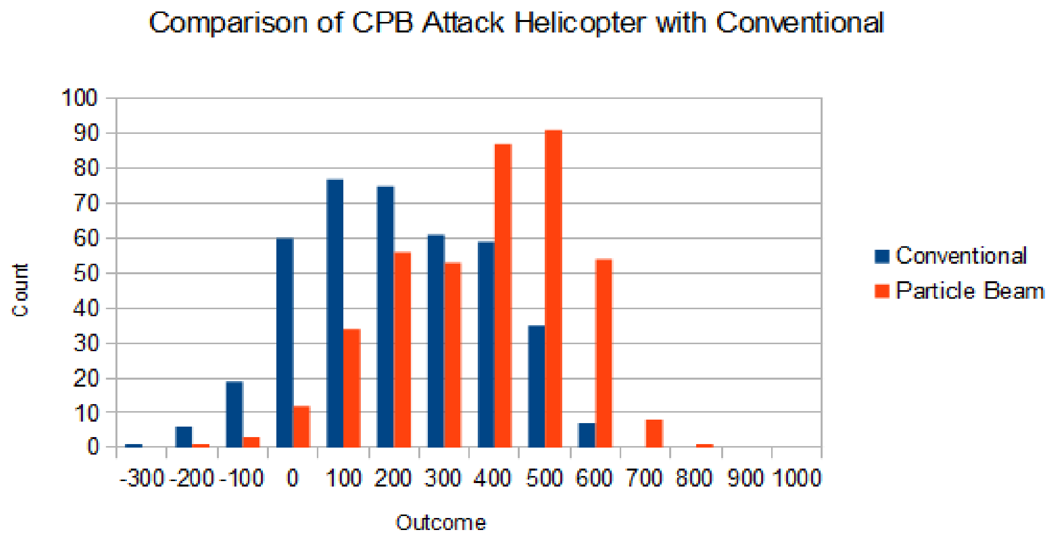


Figure 4.4. Comparison of outcome between Conventional and Particle Beam

4.3 High Power Microwave Weapons in Naval Campaigns

The scenario we will use will consider a 3 destroyer SAG (Surface Action Group) in the Strait of Hormuz defending itself against an enemy attack by anti-ship cruise missiles launched from both ground sites as well as from aircraft. The results given here are from [T16]. Figure 4.5 below shows an overview of this scenario.

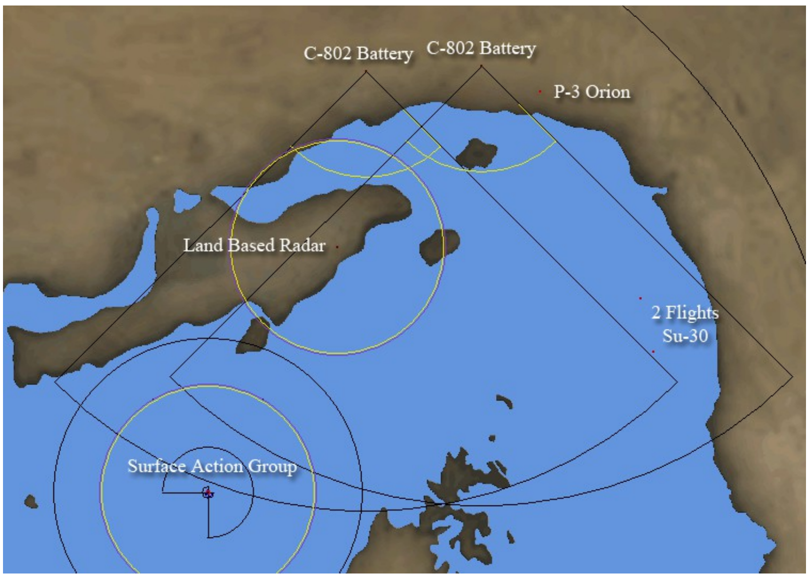


Figure 4.5. Overview of HPM Scenario.

The assets for each side consist of:

- 3 Arleigh Burke III destroyers equipped with a 1 GW HPM in place of the RIM-162.
- 2 enemy land-based C-802 batteries each with 6 C-802s.

- 1 enemy P-3 Orion providing airborne radar surveillance as shown below.

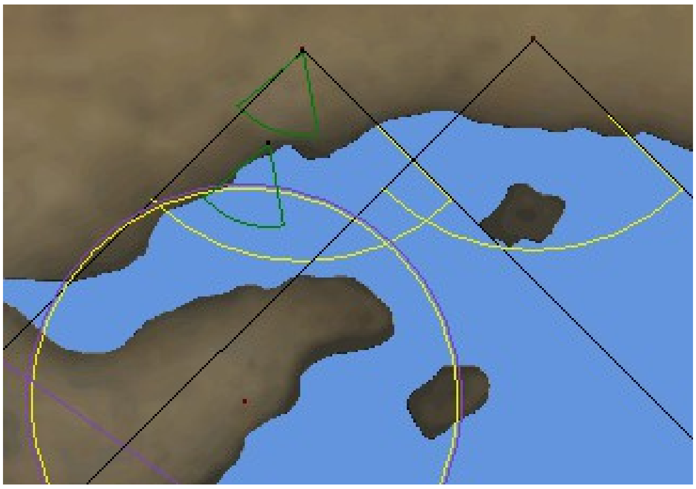
- 2 flights of 2 Su-30s with each aircraft equipped with 6 Kh-31 Anti-Ship Cruise Missiles as shown below. The aircraft are flying low-altitude to avoid the SAG radar.

The scenario is run using AI (Artificial Intelligence) logic with no manual intervention. It is run in two modes: on-screen providing real-time visualization for verification and insight into the results, and batch-mode to provide aggregate results for analysis.

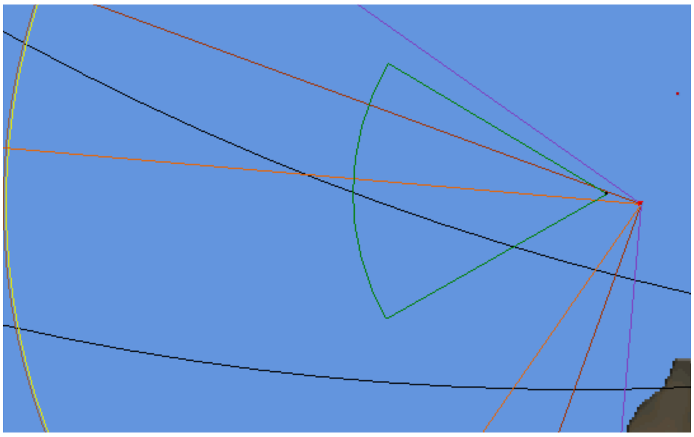
Note that in the conventional case using 8 RIM-162 missiles on each destroyer, the enemy already has more AShCM (36) than the SAG has anti-missile missiles (24). In the conventional scenario, the SAG must necessarily take hits and losses.

When run interactively on the screen, the scenario provides a timeline to events as follows. All times are wall clock times relative to a scenario start time of 12:00.

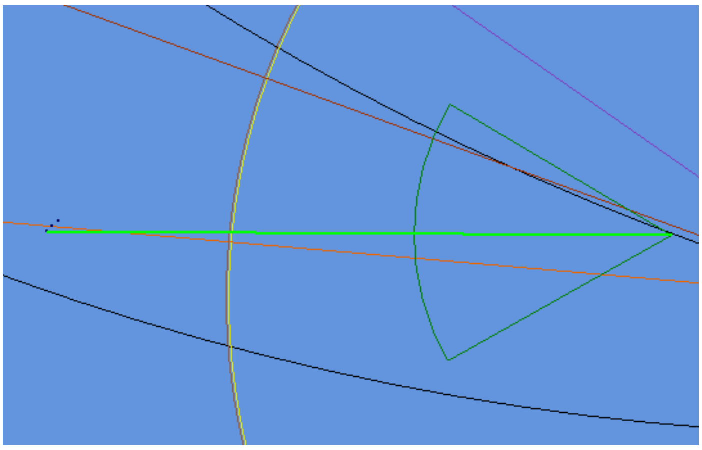
- 12:00 – At scenario start, the SAG is just outside the range of the land-based C-802 batteries but within radar range of the P-3 and thus detected by the enemy.
- 12:02 – The SAG comes within maximum range of the land-based batteries which begin firing C-802s. These are fired using inertial guidance as the range is outside the range of terminal guidance as shown below.



- 12:05 – The SAG comes within range of the Kh-31A and the aircraft begin firing over the horizon using inertial guidance as shown below.



- 12:05 – The first Kh-31A comes within range of the HPM and the destroyers begin firing as shown below.



- 12:06 – The first land-based C-802 fired missiles appear within range of the HPM and the three ships of the SAG defend themselves against both land-based and air-launched missiles.
- 12:07 – As the Su-30 appear over the horizon, the ships in the SAG defend against them

using a combination of shots from the HPM weapon and firing SM-2 air defense missiles.

- 12:10 – The missile threat from both the aircraft AShCM and land-based C-802 of the first battery is neutralized with no ship damage.
- 12:16 – The SAG enters the maximum range of the second C-802 battery and it begins firing.
- 12:21 – The C-802s from the second battery appear within range of the HPM weapon and the destroyers begin firing.
- 12:22 – The final C-802 missile is eliminated and all threats to the SAG are gone.

Finally, the scenario was run in batch-mode so aggregate results could be obtained that then took into account the random nature of any single outcome. For this purpose, the scenario was run 1000 times. In no instance were the enemy AShCM able to overwhelm the destroyer's HPM defenses and cause damage to the ships. Indeed, in the case of the air combat report, it was shown that even for a UAV with an 8 second recharge rate and a 40 dBi antenna, there was a 99.7% self defense probability against incoming missiles. In this naval situation, the three destroyers combined generate a fire rate close to 1 per second and together with the modeled RF Upset probabilities, provide completely adequate protection against the missile threat assumed here.

5.0 High Power Microwave Weapons in Modern Air Power

This analysis will use scenarios from the *Modern Air Power* simulation *War Over The Pacific* which looks at future air operations in the western Pacific in the 2020 timeframe. These results are taken from [T1]. A screen shot showing a typical scenario from this simulation is shown in Figure 5.1.

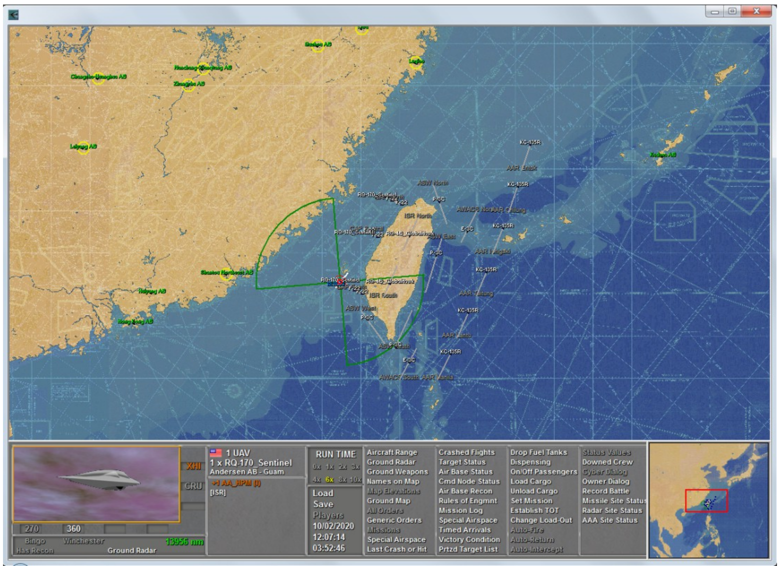


Figure 5.1. Screenshot of scenario from *War Over The Pacific*

5.1 Baseline Scenario

The baseline scenario is taken from the classic RAND study of air combat over the Taiwan Strait.

In this scenario, we assume the following US forces:

- 12 F-22 tasked with air superiority over the Taiwan Strait.
- 4 P-3C tasked with anti-submarine warfare around the island of Taiwan.
- 2 RQ-4B tasked with ISR over the island.
- 2 E-3C tasked with ISR in orbits behind the island.
- 6 KC-135R for refueling well behind the island.

We start this scenario with these forces against an attacking enemy force based on conventional assets including the J-11 and Su-30 backed by supporting ISR and refueling assets.

Using this baseline scenario, we begin by generating the first set of outcome results. It is important to understand that the baseline scenario has several limitations for US forces:

- The relatively small number of F-22s, faced with a much larger number of enemy aircraft, do not possess sufficient air-to-air missiles, even with the most optimistic estimates of their effectiveness, to prevent the incursion of enemy aircraft into the US operations area.
- The distances involved in the western Pacific between Taiwan and US bases at Kadena and Andersen are a deterrent to maintaining sufficient F-22 airborne over the Taiwan Strait to counter the enemy attack.

This scenario was first investigated as part of the John Tiller Software Phase I STTR for AFOSR/AFRL on "Innovative Combat Simulation to Craft Tomorrow's UAV Operational Doctrine", Program Manager David Ross of AFRL, in 2010 (reference AFRL-RI-RS-TR-2011-102). The scenario was developed by Lt. Col. Gary Morgan USAF (ret) to demonstrate what impact the introduction of enemy UCAVs would have on US air superiority efforts over the Taiwan Strait.

In the original JTS Phase I STTR on UAV doctrine, this limiting situation was referred to as "Missile Critical" indicating that the US could not put enough aircraft airborne over the Taiwan Strait to even have as many missiles on those aircraft as the enemy had aircraft itself.

In what follows, we compare a given scenario outcome with the effect that a particular change has on that outcome. The results are generated in aggregate using batch runs of *Modern Air Power* on a Linux cluster at the University of Alabama in Huntsville by Dr. John Rushing and then presented in the form of a histogram. In each histogram, the following should be noted:

- Outcomes to the **right** favor the US while outcomes to the **left** favor the enemy.
- Each figure consists of two histograms: the **blue** histogram represents the outcome **before** the change while the **red** histogram represents the outcome **after** the change.
- A shift to the **left** of the red histogram therefore represents a change which benefits the enemy while a shift to the **right** represents a change which benefits the US.

5.2 Introduction of Enemy UCAVs

The first change we will make to the baseline scenario is to introduce a number of enemy UCAVs based on the following concepts, first developed as part of the JTS Phase I STTR on UAVs previously mentioned:

- The Ba-5 UAV is a development based on the J-5, which was a copy of the MiG-15. We hypothesize that it would be possible to convert these into autonomous UCAVs by adding two 250 kg FAB-250 bombs and use these to attack Kadena AB by flying to the base and crashing into it. This UAV development however is not specifically addressed in this report.
- Likewise we hypothesize that it would be possible to convert the large number of otherwise unused J-7 (copy of MiG-21) aircraft to be autonomous UCAVs each equipped with 4 short-range IR PL-9C missiles and OLS-35 IRST sensor pods. These UCAVs would be programmed to fly a predetermined ingress path and then fire at aircraft they detect following that.

Based on the introduction of these J-7 UAVs into the baseline scenario, we then rerun the scenario to generate a new set of outcomes shown in Figure 5 as the red histogram.

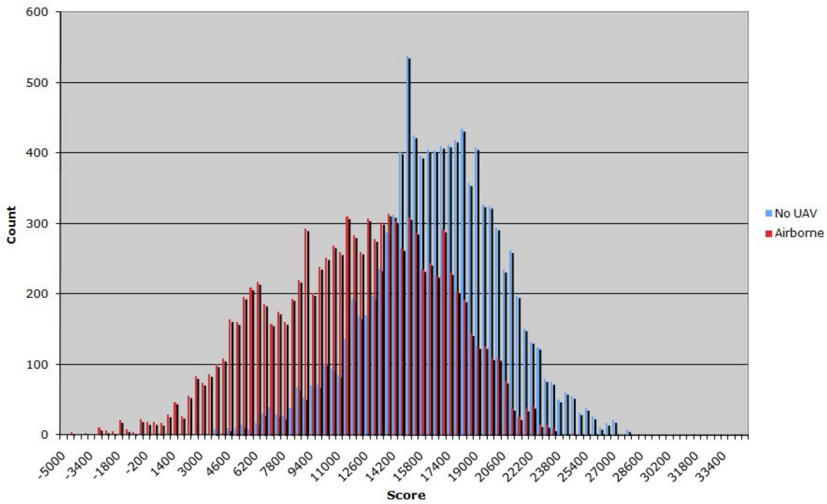


Figure 5.2. Effect of adding enemy UCAVs on outcome.

Note that the introduction of enemy UCAVs has made a bad situation in the baseline scenario even worse. What is seen when the scenario is run interactively on the screen is that the F-22s quickly become Winchester (out of ammo) or Bingo (out of fuel) simply countering the enemy UCAV incursion. Following that, the enemy conventional aircraft, following behind their UCAVs has a much easier time penetrating the US air operations area and targeting US HVA (High Value Assets) such as the E-3 and KC-135.

5.3 Introduction of US HPM-Equipped UCAVs

We next look at the effect on the outcome of adding 3 HPM-equipped UCAVs to the US force. In this version, they are deployed in static orbits forward in the deployment of US assets, similar to the deployment of F-22s. In this scenario, they are used simply as a "missile sponge" against the enemy threat. Further, in this scenario, we leave the enemy air doctrine alone and assume that these aircraft would be targeted by the enemy given their deployment up front.

The results of this change are shown as the red histogram in Figure 5.3. Note the dramatic effect this has on the outcome by virtue of the fact that so much attention and missiles goes into attacking the HPM UCAVs which are very much able to defend themselves.

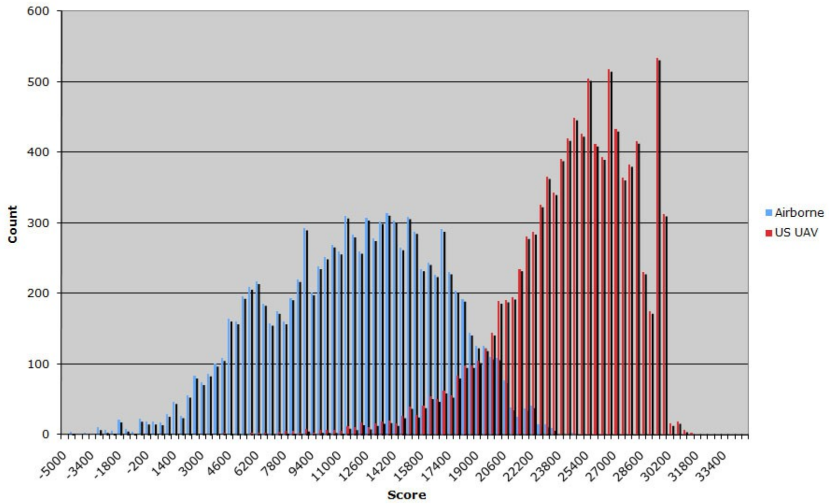


Figure 5.3. Effect of adding US HPM UCAVs on outcome.

5.4 Change to Enemy Doctrine With Respect to US UCAVs

Based on the previous results, it is clear that a failing of the enemy doctrine is to attempt to attack the US HPM UCAVs. Given their 99.7% ability to protect from enemy missiles, the US UCAVs are best avoided by the enemy. We next assume that it is very obvious to the enemy which aircraft that they are facing are equipped with HPM weapons. Either by ELINT or by detecting the HPM pulse, we assume that the HPM UCAVs are quickly identified as such by the enemy and that their countermeasure is to avoid these as much as possible. Given that the US UCAVs are deployed in static orbits in this scenario, this has a dramatic benefit to the enemy, shown as the red histogram in Figure 5.4 below.

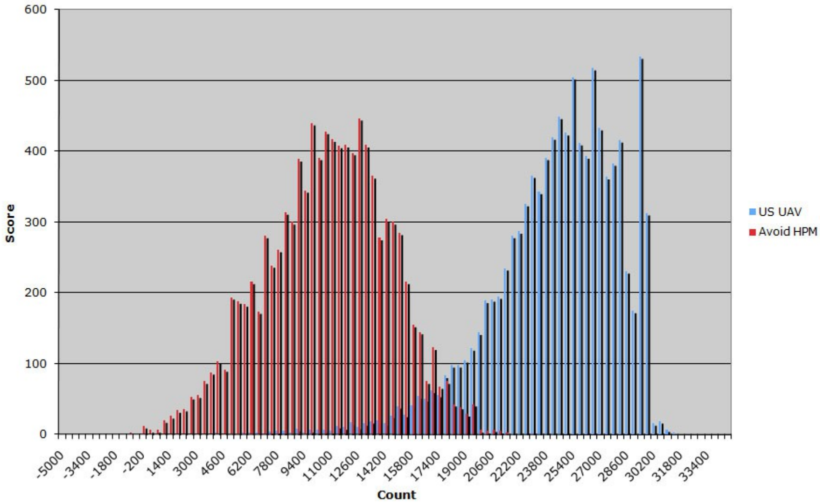


Figure 5.4. Effect of changing enemy HPM counter doctrine on outcome.

5.5 Change to US UCAV Doctrine

Finally then, it is obvious that leaving the US HPM UCAVs in static orbits no longer works with the current enemy doctrine. We next change US UCAV doctrine so as to assign the HPM UCAVs the mission of Air Superiority. In this role, they will actively pursue and engage enemy aircraft. This counter to the enemy counter has a positive effect on the outcome, shown as the red histogram in Figure 5.5. When running this scenario interactively on the screen, it is seen that the US UCAVs would benefit from a higher speed to make it easier to intercept enemy aircraft.

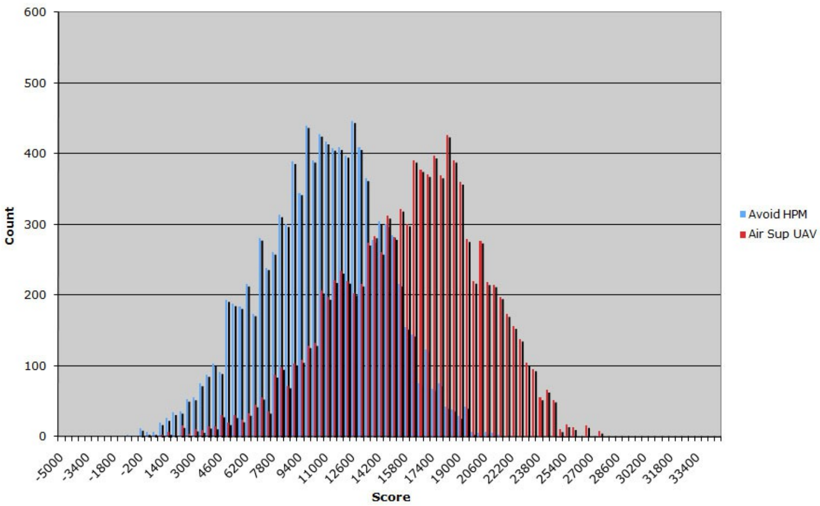


Figure 5.5. Effect of changing US UCAV doctrine on outcome.

6.0 Mathematical Analysis

Research by John Tiller Software and the University of the South has produced a number of analysis techniques particularly suited for understanding the dynamics of simulation outcomes and for calculating the risk associated with decisions made relative to these outcomes.

6.1 Tipping Points

In the research paper [P8], Dr. Cavagnaro of the University of the South and John Tiller of John Tiller Software establish the fundamental properties of a notion of "Tipping Point" based on curvature. The curvature of a function at a point is given by the equation:

$$\kappa(x)=\frac{y''(x)}{(1+y'(x)^2)^{3/2}}$$

The geometric basis for this calculation is illustrated below in Figure 6.1 where the radius of the circle equals the curvature of the curve.

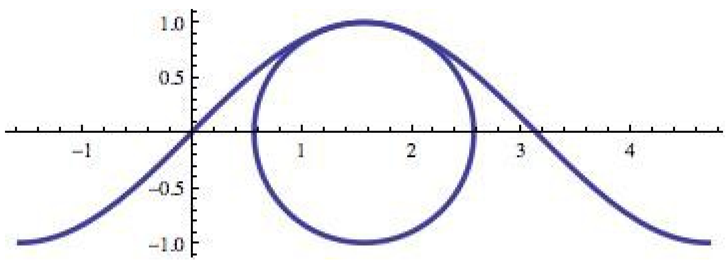


Figure 6.1. The geometric basis for the calculation of curvature.

In the paper on Tipping Points by Cavagnaro and Tiller, a notion of "Tipping Point" is introduced based on the concept of the maximum value of the absolute value of curvature (Curvature may be positive or negative). It is important to understand the curvature is not a dimensional-less quantity and depends on the relative scaling of the axes of the function. In the research paper this is addressed with a notion of a relative scaling parameter R which then determines various curvature values and their corresponding maximum. The dynamics of this is illustrated below in Figure 6.2 which shows both the second derivative of a particular function and a number of curvature functions based on values of R.

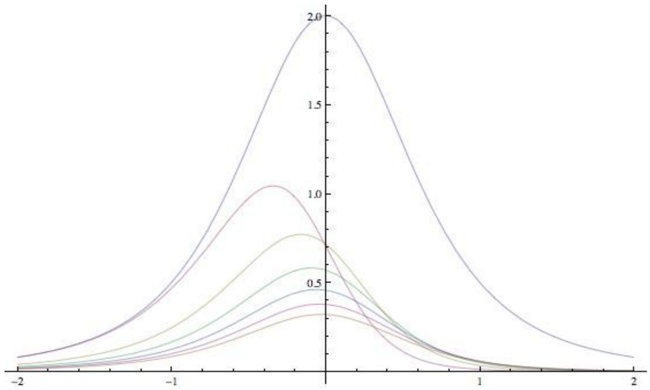


Figure 6.2. Second derivative (highest curve) together with curvature functions based on increasing R.

Also in this research paper, the calculation of the Tipping Point of simulation results was generated via the concept of Levenberg-Marquardt curve fitting. That is, given simulation results that provide a number of discrete points, it is possible to calculate a curve fitting of those points and from those points calculate analytically a Tipping Point of the curve. How this was done in the paper is illustrated below in Figure 6.3.

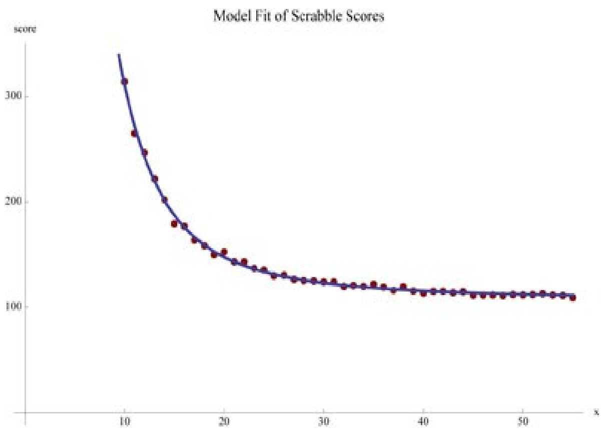


Figure 6.3. The Levenberg-Marquardt curve fit of simulation result points.

A key result is then which curve to use in this fitting. In the paper, a critical function for this purpose is defined as the "TC Tipping Point Model Function":

$$y(x)=a\left[\frac{(x-b)}{c}\left(\arctan\left(\frac{x-b}{c}\right)+\frac{\pi}{2}\right)+1\right]+d$$

The TC Tipping Point Model Function.

This function has extremely important properties with respect to the calculation of maximum second derivative, a related concept called "Hard Tipping Point", and that of Tipping Points based on curvature, called "Natural Tipping Points".

The fundamental application of this research to military operations is in the following concepts:

- Given a combat situation in which the enemy is deploying a new technology which results in an advantage to them, is there a Tipping Point in the outcome curve which indicates that a certain point in that deployment the advantage to the enemy becomes a situation that cannot be compensated for? The answer to this question can be derived through the generation of simulation results and then calculating possible Tipping Points in the Levenberg-Marquardt fit of the TC function to those results.
- Given a deployment situation where we have the option to deploy a variable number of high value assets, is there a Tipping Point in the benefit associated with that deployment where the further increase in deployment above a certain value results in diminishing results in the benefit? The answer to that question can also be answered with the previously stated calculation.

Future research will look for further application of this concept of Tipping Point in the outcomes and related effects of mission level and strategic level scenario results that would indicate significant transitions in those outcomes and effects. Such an investigation could result in answers to questions such as:

- Suppose it is determined that the utilization of a particular advanced weapon has an adverse impact on the attitude of a given populace towards us. Is there a Tipping Point associated with that impact where our ability to compensate for those negative results is greatly diminished? If so, then we should be aware of that Tipping Point and work towards avoiding that outcome.

An associated concept developed in the research paper is that of "Tipping Interval". Based on the notion of inflection points, a Tipping Interval will bracket a Tipping Point and give you an indication of where the dynamics of a given outcome are starting to change and then final transition. Utilized in the previous scenario, it would be prudent to know the Tipping Interval of this effect and work towards avoiding even that interval so as to prevent the transition to an unrecoverable negative outcome.

6.2 Risk Analysis

In a second research paper by Cavagnaro and Tiller [P6], the concept of "Continuous Risk" is introduced. The idea is based on the concept that the integral of a curve from negative infinity to a specific value is a measure of the "downside risk" associated with that outcome as illustrated below in Figure 6.4.

By introducing this concept it is then possible to calculate the risk associated with simulation results and to quantify the effect that command decision might have on this risk in actual combat situations.

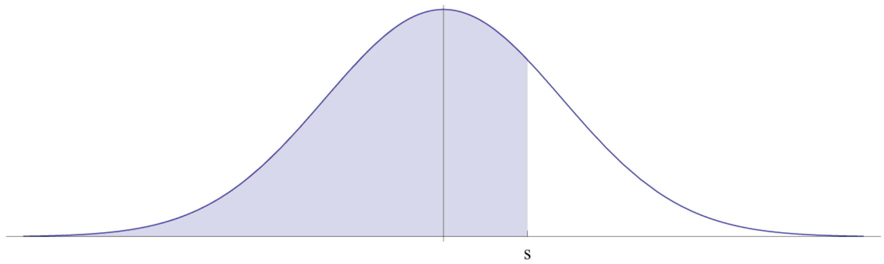


Figure 6.4. The integral from negative infinity to a specific value s as a measure of continuous risk.

As was done previously, the transition from discrete simulation results to continuous curves which have a calculable integral is given by Levenberg-Marquardt curve fitting but in this case using Gaussian Distributions as illustrated below in Figure 6.5.

Indeed, Figure 6.5 shows an example of this curve fitting applied to scenario outcomes of a UAV scenario developed as part of the previously mentioned STTR project by John Tiller Software and the University of Alabama at Huntsville.

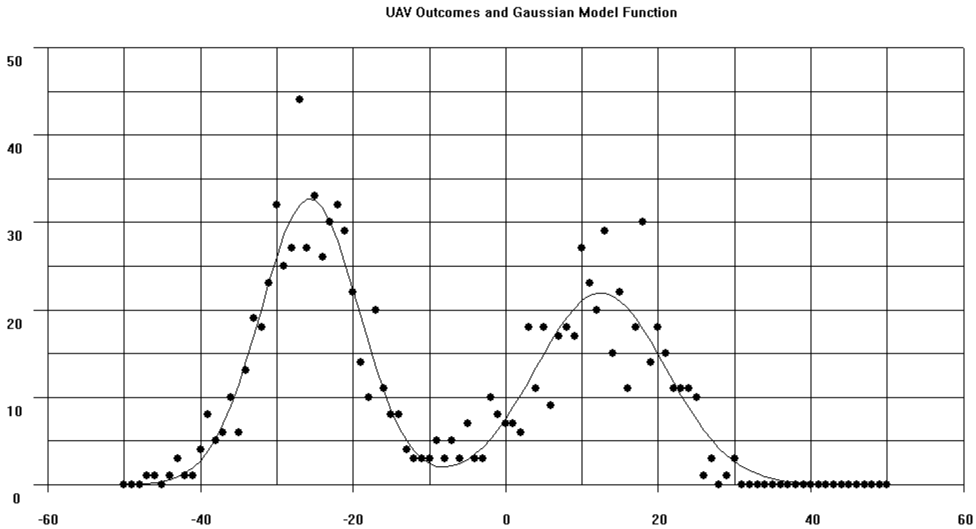


Figure 6.5. Bi-modal Gaussian curve fitting to UAV scenario outcomes.

Having established this concept and associated calculations, the question then becomes if we can quantify the risk associated with curves such as the Gaussian and use these to provide insight into how military decisions affect that risk value. A fundamental result from the paper [P6] is in the calculation of "Downside Risk" (risk calculated to the average) of a Gaussian function:

$$R=\frac{\mu}{2}+\frac{\sigma}{\sqrt{(2\pi)}}$$

where R is the downside risk, μ is the average of the Gaussian, and σ is the standard deviation.

This results provides fundamental insight into how military decisions affect risk as given in two examples. The first more obvious one is how a change in standard deviation with no change in average affects risk as illustrated below in Figure 6.6.

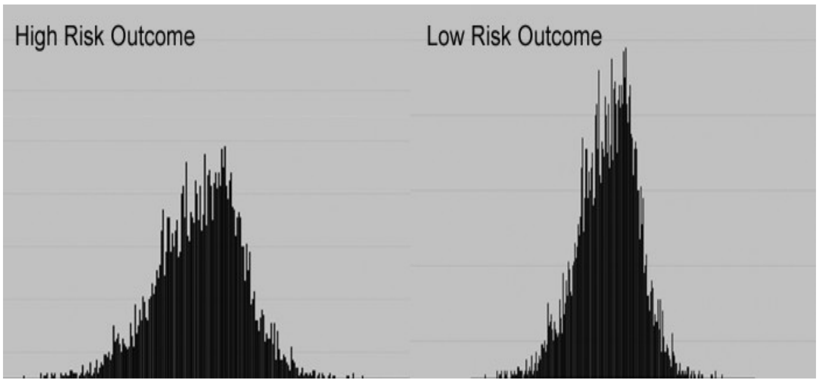


Figure 6.6. Illustration of high-risk and low-risk simulation outcomes.

While it is clear from the figure that the low risk outcome produces less variation in the results and thus provides a military commander more assurance in the outcome, the fundamental calculation of Gaussian risk previously given provides a quantification of that difference.

A less obvious insight is in the context of the following military situation:

- As a military commander in a given situation, you are given the choice between two COAs (Courses of Action). COA 2 has a high average outcome than COA 1 but has more variation in the outcome by virtue of a larger standard deviation. How do you as commander make an informed decision between these options?

The fundamental calculation of Gaussian risk provides a quantification of the risk associated with these two choices and numerically identifies which one is preferable from the viewpoint of risk. In particular as identified in the research paper:

> *Average is more important to risk than is variation.* If you are given an option which increases the average outcome and also increases the variation in results, then you are better off accepting that option as it will increase the value of risk. Conversely, if a strategy offers smaller variation but also a smaller average, all things being equal, you are better off declining that option as it will increase your exposure to risk.

7.0 Risk and Tipping Points in Air Operations

This section looks at the application of the mathematical analysis discussed in the previous section to the specific issue of air operations and applies the theory of risk assessment and tipping points to generate insight to that situation. These results are taken from the paper "Tipping Point and Risk Assessment of Force Allocation and Countermeasures in Air Operations" [P1].

A screen shot of one of the scenarios used in this paper is shown in Figure 7.1. We consider modern air superiority scenarios based on typical US air assets such as the F-22 versus contemporary enemy asset such as the J-11. We begin with a standard scenario to establish a base line for analysis. Each resolution of a Modern Air Power scenario produces an outcome which varies due to the stochastic nature of the resolution which uses probabilities and random number generation to adjudicate the result of air combat. Each outcome represents a victory point level by tracking air losses, associating values to each of these, positive values for enemy air losses, negative values for friendly losses, and looking at the final summation at the end of the scenario. By rerunning the same scenario a large number of times in batch mode, we thus produce a distribution of outcomes. By varying the number of US aircraft allocated to the scenario we can then look at how the average of this distribution varies by that number.

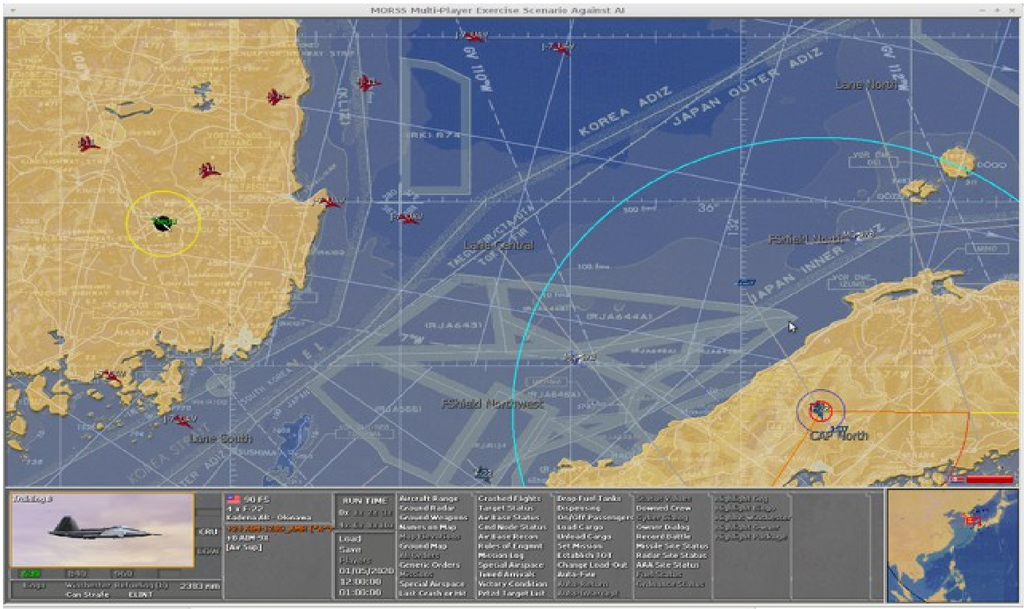


Figure 7.1. Scenario used for air operations analysis.

A typical result from this approach is shown in Figure 7.2. This histogram results from running the baseline scenario approximately 600 times and formulating a histogram of the outcomes. In this histogram, outcomes further to the right represent outcomes more favorable to the US side while outcomes to the left represent outcomes unfavorable to the US side. More iterations of the scenario would smooth the histogram but at a certain point we conclude the iteration of the scenario and curve fit the histogram using one particular mathematical curve.

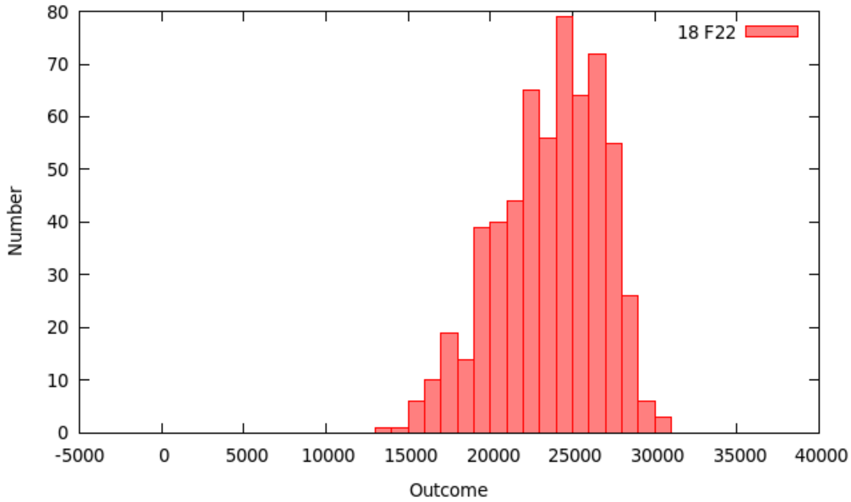


Figure 7.2. Baseline scenario outcome in histogram form.

Figure 7.3 shows the result of having curve fit the histogram using a conventional Gaussian distribution.

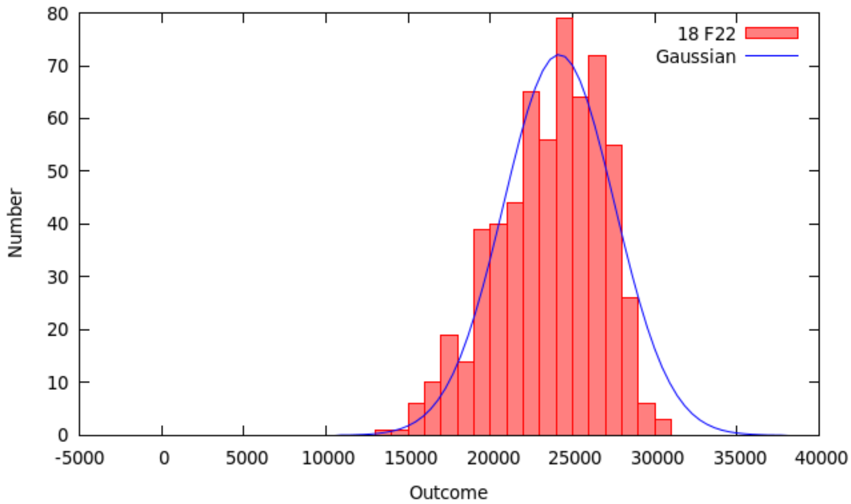


Figure 7.3 Histogram results curve fit with a gaussian distribution.

The second scenario we consider then looks at how the outcome will vary if the enemy adds a certain number of UCAVs (Unmanned Combat Air Vehicles) to their force. In this case, we consider conversions of the J-7 aircraft to a UAV, each equipped with PL-9 air-to-air missiles. We assume the enemy deploys a certain number of these in flights which are in the first wave of the enemy's air attack. Again as before, we then vary the number of UCAVs deployed by the enemy and analyze how the outcome of the scenario varies as a result of this.

The final scenario then looks at the introduction of HPM equipped US UAVs. This future aircraft is based on the characteristics of the current day X-47B equipped with a 1 GW HPM weapon. It is determined that the weapon could have a firing rate of once every 8 seconds and have an effective range for RF Upset of 8 nautical miles. In this scenario, we consider how the introduction of that capability affects the outcome of the previous scenario utilizing enemy UCAVs. Further, we analyze the dynamics of that outcome and conclude an important point about the application of game-changing technology.

7.1 Force Allocation Analysis

We consider the problem of force allocation relative to a specific air superiority scenario and derive the first of our three principles. The force allocation problem is relative to the number of F-22s we allocate to this scenario and how that affects the outcome. In particular, we vary the number of F-22s in the scenario from 3 to 30 in discrete steps and in each case, iterate the scenario a certain number of times to generate a histogram to which we curve fit a gaussian curve as shown in Figure 7.4.

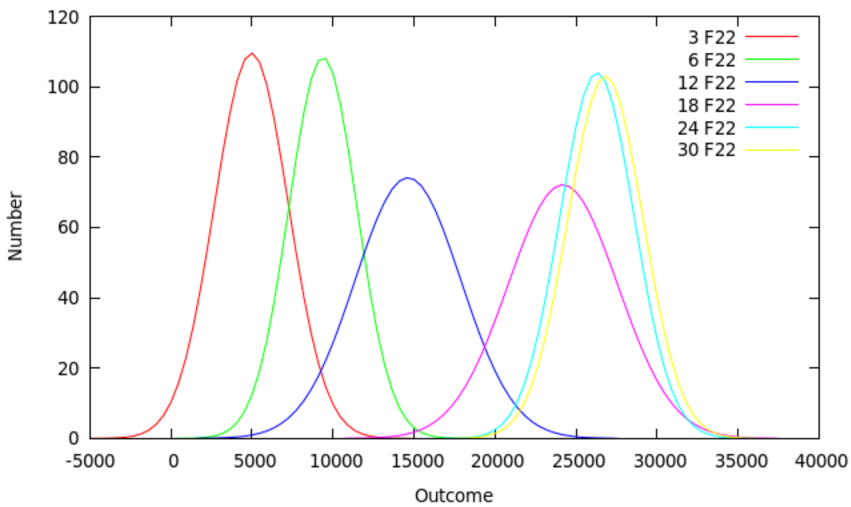


Figure 7.4. Gaussian curves fit to outcome histograms of varying numbers of F22s.

From each gaussian curve we then compute the average value of that curve. The average value of the outcome plotted by the number of F22s versus the outcome value is then plotted in Figure 7.5.

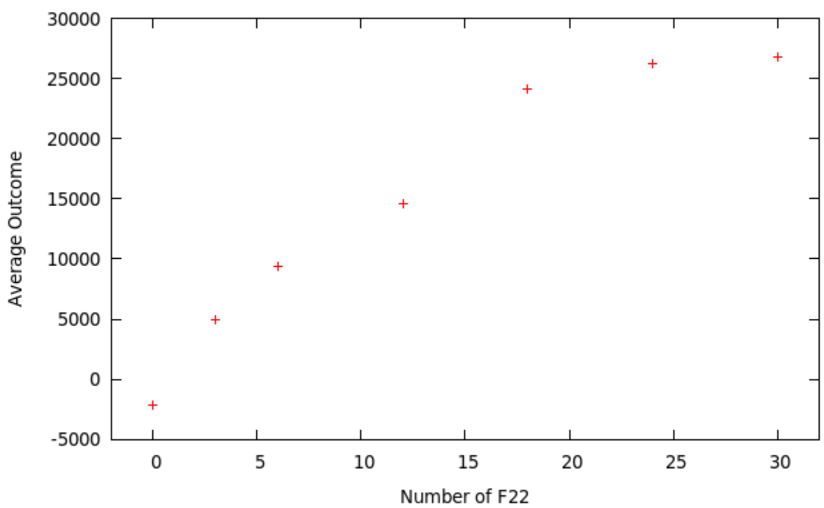


Figure 7.5. Plot of gaussian curve averages using number of F22s versus outcome value.

The average value points are then curve fit using the TC Model function to arrive at the curve shown in Figure 7.6.

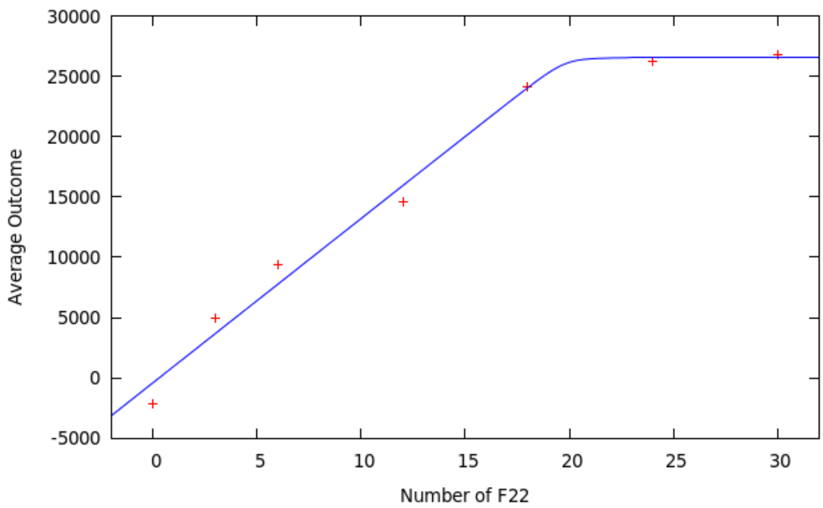


Figure 7.6. Curve fit of TC Model Function to average outcome points.

Given the nature of the TC Model function as shown in Figure 7.6, we arrive at our first observation based on the outcomes generated by the allocation process in this scenario associated with the tipping point at about 20:

> **Observation 1**: *Winning Tipping Point.* If you start from a point of dominance, you may be able to decrease your effort associated with that to a certain point and not see any decrease in the outcome, after which you may transition through a Tipping Point and suffer a continued reduction in the outcome from that point onward.

7.2 UAV Analysis

In this section we consider how enemy countermeasures might affect the outcome of the air superiority scenario. In this case, we consider the number of F22s in the scenario fixed while varying the allocation of enemy UAVs. As described before, in this scenario we utilize an enemy UCAV represented by a J-7 converted to UAV equipped with PL-9 air-to-air missiles. These UCAVs are autonomous in the scenario, flying in flights of 8 in the first wave of the enemy's air attack. This section will describe not only an important issue about tipping points but also about risk assessment relative to this analysis.

To begin with, consider the two outcomes generated by having 0 enemy UAVs in the scenario compared with 24 UAVs. The two plots generated from these are shown in Figure 7.7. What is critical to notice about these plots is that they have approximately the same average but different standard deviations.

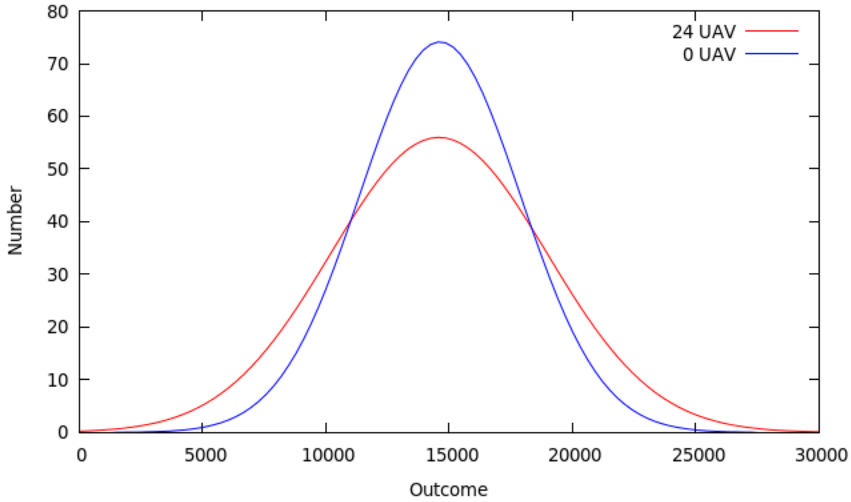


Figure 7.7. Results from two scenarios with different number of enemy UAVs.

Therefore, by considering the two plots shown in Figure 7.7, we see that even though there is no significant difference in the average outcome of the two curves, we understand that the curve associated with 24 UAVs to have a higher risk value and thus a situation that we wish to avoid.

Likewise as before, by then varying the number of enemy UAVs in discrete steps we generate separate gaussian curves associated with each one as illustrated in Figure 7.8.

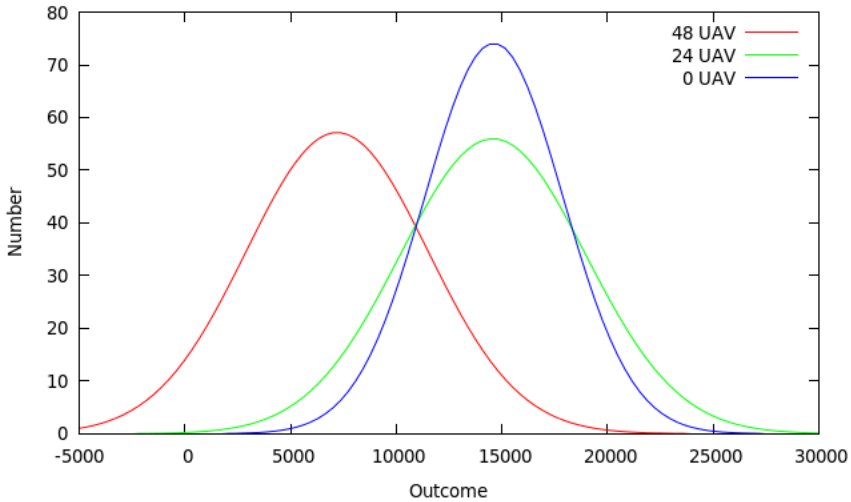


Figure 7.8. Multiple gaussian curves fit to UAV outcome histograms.

Having done this we then compute the average of each curve and plot those with number of enemy UAVs versus the average value as shown by the points in Figure 7.9. And again as before, we can then compute a TC Model Function curve fit to these points as shown by the curve in Figure 7.9.

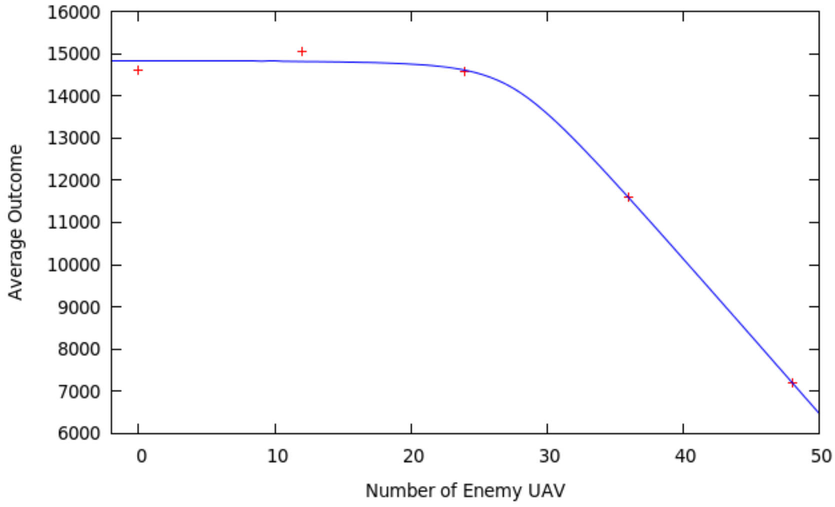


Figure 7.9. TC Model Function curve fit to results by varying number of enemy UAVs.

Combining the two conclusions associated with the risk and tipping point of the enemy UAV curve, we arrive at our second observation:

> **Observation 2**: *Losing Tipping Point*. If the enemy increases their efforts, you may at first see no change in the outcome, but you may in fact suffer increasing risk during this time. However after a tipping point is reached, you may then see a continued reduction in the outcome from that point onward.

7.3 Use of High Power Microwave UAVs

In this section we now fix both the number of F22s and the number of enemy UAVs and apply a US countermeasure. This countermeasure is given by the deployment of three US UAVs equipped with HPM weaponry. We consider a single scenario in this section based on this order of battle.

The outcome histogram associated with this scenario is shown in Figure 7.10. It is critical to notice that while previous outcome histograms had a symmetric shape well fit by a gaussian curve, this histogram has a distinctly skewed shape which would not fit well with a gaussian. This kind of outcome indicates that the scenario is generating outcomes that are nearing the upper limit of what is possible given the forces involved. That is, we will consider such an outcome histogram to represent a situation where one side is dominant over the other.

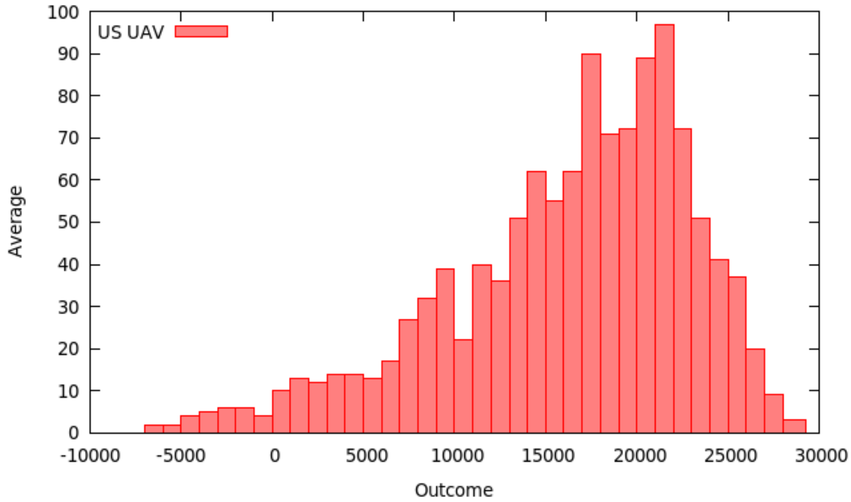


Figure 7.10. Scenario outcome histogram resulting from the introduction of US HPM UAVs.

To fit such a skewed histogram, we need to consider another curve other than the gaussian. As established before, the log-normal curve can be consider as resulting from a multiplicative random walk and thus results from a skewed process where there is a bound in the values in one direction while being unbounded in the other. Thus, we strive now to curve fit the outcome histogram with a log-gaussian curve and this is shown in Figure 7.11.

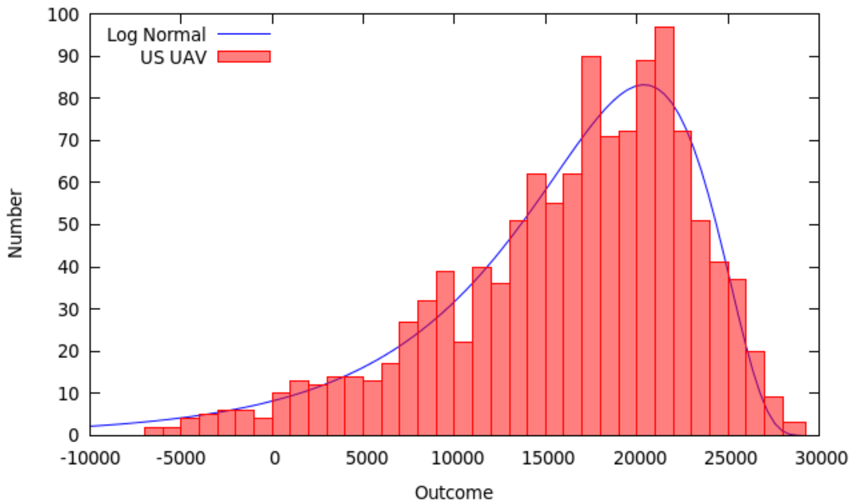


Figure 7.11. Log-Normal curve fit to outcome histogram.

Having achieved this fit with the log-gaussian, we can derive an important characteristic of this outcome. The log-normal curve is known to be a fat-tailed distribution. As such, the tail decays at a slow rate which results in characteristics to the curve as described in the reference. Among these is the this high likelihood of catastrophic events. In our case, such catastrophic events are represented by major defeats given by points in the tail of the curve. This understanding results in our third observation:

Observation 3: *Game-Changing Risk.* Even with the introduction of a new approach or technology that results in a game-changing difference in the outcome in your favor, you may still be vulnerable to significant downside risk. As the outcome curve illustrates, while you may enjoy an expectation of a favorable outcome you must still be aware that significant defeats are not only possible but a meaningful possibility.

8.0 Advanced Effects

Figure 8.1 below diagrams one possible approach to a new architecture relative to the existing wargame engine and AI structure.

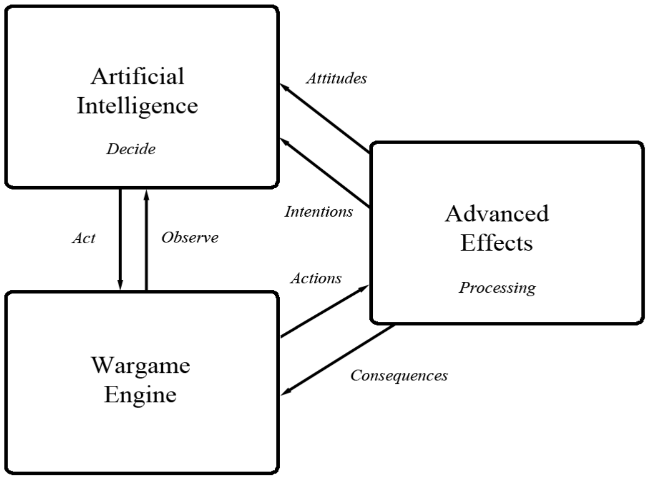


Figure 8.1. Possible architectural design for future research.

In the implementation shown in Figure 8.1 above, the interactions are described by:

- **Actions** – Events taking place in the Wargame Engine cause changes in the Advanced Effects module. These events can be combat related or can be based on other actions associated with the Wargame Engine.
- **Consequences** – The changes these Actions trigger in the Advanced Effects module then cause certain immediate state changes in the Wargame Engine. For example, the firing of a Directed Energy weapon in the Wargame Engine may trigger effects in the Advanced Effects engine which result in a morale change back in the Wargame Engine.
- **Attitudes** – Based on issues such as cultural factors, the Advanced Effects module may convey to the AI Module certain facts which influence how the AI Module makes decisions. For example, based on cultural factors, the AI Module may conclude that suicide attacks are an acceptable action to decide to take, whereas in other situations the AI Module might conclude that the cultural factors discourage such attacks.
- **Intentions** – In addition to immediate Consequences, Actions can trigger Intentions in the Advanced Effects engine which would then be used by the AI Module in its decision making. For example, if the use of a Directed Energy weapon in the Wargame Engine triggered anger in the Advanced Effects module, then this may result in an Intention to

attack. Such an Intention would then result in the AI Module deciding to plan and execute that attack.

As such this associated research represents a foundation upon which future research into advanced effects can be pursued.

9.0 Research into Wargame PMESII Representations

A research effort was initiated during this project to investigate and conduct initial implementation of wargaming representations of PMESII (Political Military Economic Social Infrastructure Intelligence) effects. After reviewing current approaches in other research efforts, a previously AFOSR-funded effort by David Ross of AFRL associated with the creation of the SMITE (Successfully Managing Insurgencies and Terrorism Effectively) wargame was selected. From the Abstract of that project:

> "SMITE sought to develop a wargame to assist the examination of the applicability of new technology and TTPs and secondarily provide a modifiable tool useful for training, educating and assisting American and allied planners committed to COIN/CT & AT/FP efforts (hereafter referred to simply as "COIN"). SMITE assessed various hypotheses on how to measure progress in COIN operations; incorporating the most influential measures into planning support tools in new ways based on new ideas and technologies. Furthermore, SMITE analyzed state of the art methodologies for measuring, monitoring, and assessing COIN operations, tested them against both historical and potential COIN scenarios, and created a pen-and-paper wargame training tool as a result (see Appendix D – SMITE Rules Set 1.0 for more). Due to the broad scope and time lengths covered in the wargame, the resulting granularity is very broad."

An initial effort was conducted to realize the basis for SMITE in software and programming development occurred with the following approach:

- The programming language selected was C# for reasons of portability.
- The user interface GTK# was choosen for portability and compatibility with C#.
- Scenario-specific rules and AI were designed to be written in the John Tiller Software expert system *Clash::Reason*.

The choice of *Clash::Reason* resulted in several advantages. First, it is developed by John Tiller Software and so changes and enhancements to it necessary to support this or other efforts was made possible. The version of *Clash::Reason* written in C# was selected for compatibility with the other parts of this development. And a particularly attractive feature of *Clash::Reason* is that it can be linked with other code and called as a subroutine in that code. This meant that the framework of the development could be done in standard C# with *Clash::Reason* available to resolve specific rule sets in both the game system as well as the AI.

This effort resulted in an initial implementation of the original card-based SMITE wargame in C#

and referred to as New SMITE to distinguish it. This implementation was run using the historical Philippines scenario from the original SMITE project.

10.0 Other Contributions

Dr. Thomas Hussey and Dr. Tiller were invited by Dr. Mark Maybury, then Chief Scientist of the Air Force, to contribute a concept for the 2013 Global Horizons effort. Their concept on "Accounting for the Human Element in Air Operations Involving Emerging Weaponry" was presented to Dr. Maybury that summer at Wright-Patterson Air Force Base and included in the final report.

Dr. Tiller was invited to contribute an article to the upcoming book *Zone of Control*, edited by Pat Harrigan and Matthew Kirschenbaum, and scheduled to be published by MIT (Massachusetts Institute of Technology) Press. Dr. Tiller has been coauthoring this article with Dr. Cavagnaro of the University of the South on "The Development and Application of the Real-Time Air Power Wargame Simulation Modern Air Power" [BA1].

In the summer of 2010, Dr. John Tiller participated in the Navy CNO (Chief Naval Officer) XXIX SSG (Strategic Studies Group). That year, the SSG's topic was Directed Energy and Hypersonics. Modifications were made to *Modern Air Power* to support sea craft representations and using this, scenario analysis was done on the relative benefits of Directed Energy weaponry in three instances: defense against swarm tactics, defense against ballistic anti-ship missiles, and a surface action group encounter. A sample outcome of this analysis is shown below in Figure 10.1 illustrating the benefit of DE weapons in a defense against an enemy swarm attack.

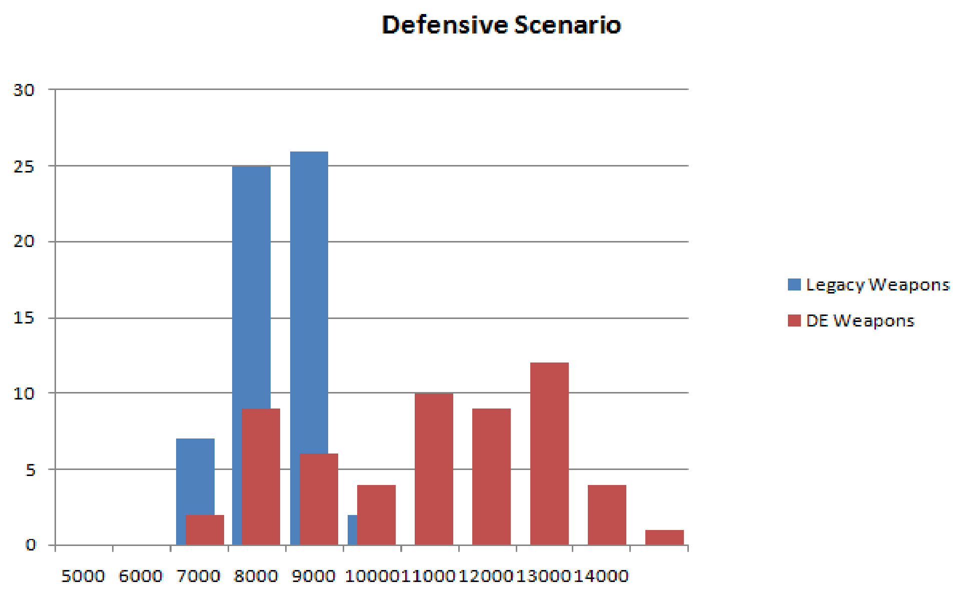


Figure 10.1. Comparison of swarm attack scenario using DE weapons versus legacy.

An investigation was conducted into potential transitions of research into microplasma lamps pursued by the University of Illinois, Urbana-Champagne [T14]. Three significant transitions of this research were identified:

- Airborne Illumination – Calculations showed that future versions of these lamps could be used with UAVs to effectively illuminate areas for both military and civilian use.
- Optical Cloaking – Lamps of this type designed to produce ultraviolet radiation could be used to provide optical cloaking protection to aircraft which may be the target of surface-to-air missiles.
- Collision Avoidance – Used on private and commercial aircraft, these lamps have an extreme photosensitivity that could be used to detect other aircraft nearby and thus aid in airborne collision avoidance.

11.0 Analysis of Suborbital Strike Spacecraft

In the spring of 2012, Capt. Daniel House wrote a Master's Thesis for the American University on the impact of a military conversion of the Virgin Galactic commercial suborbital spacecraft. In his thesis, Capt. House looked at the effectiveness of such a vehicle in the performance of deep strikes against heavily defended enemy targets versus the use of conventional weaponry. He found that due to the relative inability for enemy IADs (Integrated Air Defenses) to reach such a spacecraft, that it had definite advantages in his study.

Following this work, research was conducted using aggregate runs in this project resulting in the comparision shown below in Figure 11.1:

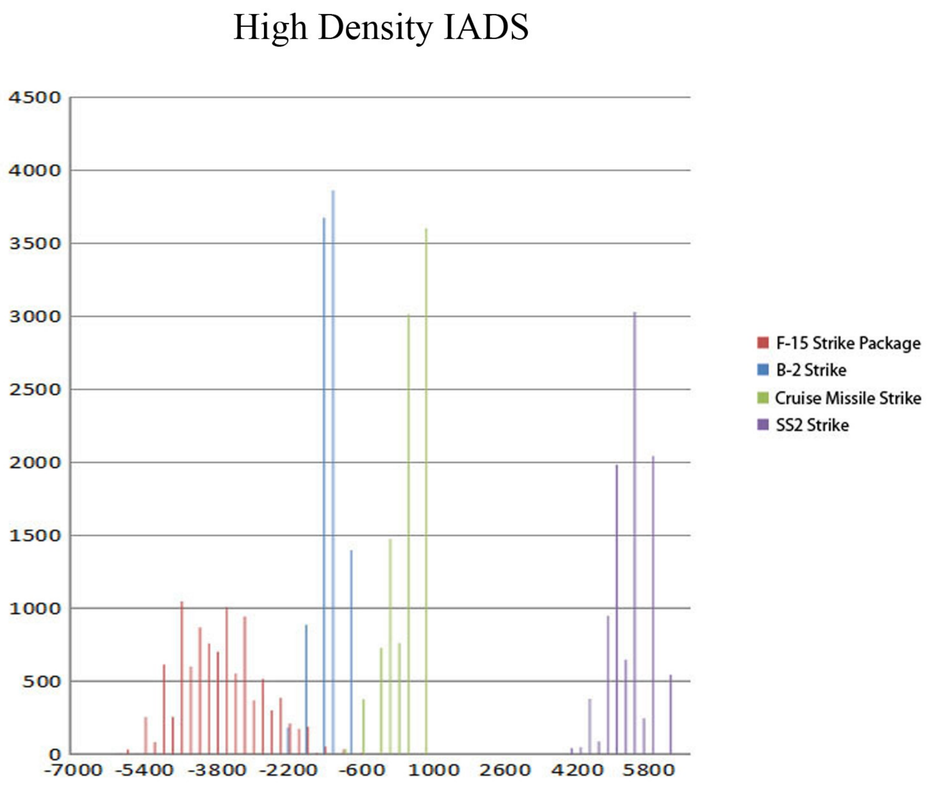


Figure 11.1. Comparison of suborbital SS2 strike versus conventional weaponry.

These results together with Capt. House's original results were written up in the paper "Wargame Simulation of Dual-Use Commercial Suborbital Spacecraft and Potential Applications to Future Warfare" [P5]. In addition, the concept was programmed using DIS (Distributed Interactive Simulation) by Dr. John Rushing and run as part of the ACE (Advanced Concepts Exercise) 13 held at Kirtland Air Force Base.

12.0 Scenario Analysis of Advanced Weaponry

Mr. David Ross, wargame consultant, analyzed scenarios of future combat and the potential impact of advanced weaponry on those scenarios. These studies, documented in [CR1] Operation Hot Asphalt and [CR2] Operation Tar Baby, looks at scenario situations in the Middle East and Western Pacific respectively. In each case, two situations are considered. First, a nominal combat situation is investigated involving coalition forces against a red enemy force. Secondly, the potential impact of advanced weaponry, particularly directed energy weapons, is considered.

In Operation Hot Asphalt, the most developed of the two scenarios, an amphibious invasion in the Middle East is studied. As given in the scenario overview:

> "The Objectives of Operation Hot Asphalt are to Clear the SOH of all threats to navigation and destroy the infrastructure which would allow such threats to reconstitute, minimizing own losses, civilian casualties and damage to non-objective infrastructure."

In this scenario, there are assumed to be large numbers of mobilized militia that oppose the landing. The consideration of a conventional attack looks at how this situation could bog down due to a reluctance to inflict heavy casualties in otherwise civilian participants. The militia as described in the scenario overview:

> "Poorly lead by locals, armed with AKs and RPGs, they grab their weapons and wait. Initially weak since they are not really expecting a fight, they rapidly mobilize and if left alone will recover rapidly. Fanatic, but not really thrilled to leave home."

The Blue side must achieve the objectives, but restricted as given in the Blue commentary:

> "Win the PR war.
>
> a. Do not rubble any city hexes
>
> b. Avoid rubbling any town or village hexes."

This together with a desire to avoid significant militia and civilian casualties, restricts the use of conventional weaponry. While able to call upon significant naval force as well as airborne assets, doing so works against the limiting constraints of the scenario.

Having established that a conventional approach to the situation has significant potential downside, with the introduction on non-lethal directed energy weaponry, the study considers how advanced weaponry could facilitate the occupation of key geographical objectives without causing excessive enemy casualties and thus avoids potential negative strategic effects.

13.0 Analysis of Wargaming and Advanced Effects

Dr. Tom Hussey, consultant with the University of New Mexico, looked at two key issues in this project:

1. How can advanced wargames benefit the military at lower cost and less time than other analysis approaches?
2. How can wargaming be used in the analysis of behavioral effects of advanced weaponry?

The results of this effort have been written up in publications [P4] and [P2] respectively. In the first report, Dr. Hussey considers the application of advanced civilian wargames and how this technology might be leveraged in military analysis. The abstract from this report states:

> "Wargames have long been pursued by the military for a variety of purposes, from training to the development of strategy and tactics. Since World War II computer technology has added new dimensions to the ways in which such wargames can be used. The same period has seen the creation of a massive civilian computer gaming industry that has developed largely separate from the military and has outstripped military capabilities in a few areas. In this paper we consider some developments within the civilian wargaming community, notably related to the adaptation for use by a broad user base, that have the potential to provide significant additional capability to the military."

The report considers so-called Serious Games and their potential application to military problems and training and also compares civilian vs. military wargames. The report concludes that there are indeed opportunities to apply serious civilian wargames to military situations and by doing so realize a significant benefit.

In the second report, Dr. Hussey looks at the possibility of doing research relative to the use of advanced weaponry, particularly non-lethal weaponry, in future warfare and how wargaming could be used in this effort. The abstract from this report states:

> "We outline an approach for assessing the benefits and consequences of advanced weaponry. We observe that recent work in understanding the indigenous population in a counterinsurgency (COIN) or stability and stabilization operation (SASO) is relevant to such an assessment and we propose that the PMESSII (political, military, economic, social, information, and infrastructure) construct can capture the response to the different actions. This can be done by using a wargame simulation to capture the physical outcomes of specific military actions using a particular set of weaponry together with a social model that updates PMESII variables based on these actions. We identify appropriate wargame simulations as well as candidate social models for this activity and we identify the

requirement for research into the response to the range of possible effects of advanced weaponry."

As a result of this investigation, one of the existing simulations evaluated in the report, SMITE by David Ross, previously described, was selected for further research in this project and has been implemented in initial form in software.

14.0 Conclusion

This research accomplished a wide variety of results dealing primarily with advanced weaponry and its representation in wargame simulations as well as the analysis of the results obtained from scenarios. These results and analysis provide insight into the potential future benefit of such weaponry as well as possible doctrine. The research, because the representations are physics-based, also identifies limiting factors in the deployment of such weaponry due to real-world constraints of power and energy.

The research also initiates the investigation into behavioral effects of advanced weaponry. These results indicate a path for future research into these effects and build on the representations and implementations of advanced weaponry and the wargame simulation technology associated with that. This research also had a number of interactions with other researchers in various areas as well as a number of significant transitions, both in military education and research as well as commercial.

Publications

[P1] Cavagnaro, C. E. and Tiller, J., "Tipping Point and Risk Assessment of Force Allocation and Countermeasures in Air Operations", submitted for publication.

[P2] Hussey, T. W., "Assessing the Benefits and Consequences of Employing Advanced Weaponry", ready for publication.

[P3] Tiller, J. A., Rushing, J., and House, D., "On a Concept of High-Powered Electronic Warfare", under development.

[P4] Hussey, T. W., "Potential Impact of Civilian Wargames on the Military", submitted for publication.

[P5] House, D., Tiller, J., and Rushing, J., "Wargame Simulation of Dual-Use Commercial Suborbital Spacecraft and Potential Applications to Future Warfare", submitted for publication.

[P6] Cavagnaro, C. E. & Tiller, J., "Continuous Probability Modifier Functions and Risk Assessment", CGAMES 2013.

[P7] Cavagnaro, C. E. & Tiller, J., "Risk and Tipping Point Sensitivity", ready for publication.

[P8] Cavagnaro, C. E. & Tiller, J., "Tipping Points and Models", International Journal of Intelligent Games and Simulation (IJIGS), 6(2), pp. 5-11, 2011.

[P9] John Rushing and John Tiller, "Rule Learning Approaches for Symmetric Multiplayer Games," *The 16th International Conference on Computer Games: AI, Animation, Mobile, Educational and Serious Games (CGAMES 2011)*, Louisville, KY, July 27-30, 2011.

[P10] Cavagnaro, C. E. & Tiller, J., "Risk Assessment and Tipping Points", International Journal of Intelligent Games and Simulation (IJIGS).

[P11] John Rushing and John Tiller, "Mission and Rule-Based Approach for Wargame Artificial Intelligence", *International Journal of Intelligent Games and Simulations*: vol. 6. no. 1, 2010.

[P12] John Rushing and John Tiller, "Object Oriented Artificial Intelligence for Wargames," *The 15th International Conference on Computer Games: AI, Animation, Mobile, Educational and Serious Games (CGAMES 2010)*, Louisville, KY, July 28-31, 2010.

Technical Reports

[T1] "Modeling the Impact of UCAV-Mounted HPM Weaponry on Future Combat, John Tiller Software Technical Report", 18 Nov 2011.

[T2] "Wargame Modeling and Calibration of Laser Weapons", John Tiller Software Technical Report, 07 Feb 2012.

[T3] "Wargame Modeling of Railguns", John Tiller Software Technical Report, 22 Feb 2013.

[T4] Wargaming Particle Beam Weapons, John Tiller Software Technical Report, 10 Feb 2013.

[T5] "A Concept for Non-Lethal Close Air Support", John Tiller Software Technical Report, 29 Dec 2012.

[T6] "An Application of Catastrophe Theory to Human Factors", John Tiller Software Technical

Report, 23 Feb 2013.

[T7] “Formulation of a Rule-Based Engine for Artificial Intelligence and Cultural Modeling, John Tiller Software Technical Report”, 08 Feb 2013.

[T8] “Military and Paramilitary Human Factor Modeling in Tactical and Operational Wargame Simulations”, John Tiller Software Technical Report, 07 Nov 2012.

[T9] “Historical Calibration and Future Results Experimentation in John Tiller Software Simulations”, John Tiller Software Technical Report, 22 Apr 2011.

[T10] “An Analysis of a Laser-Based Counter Suborbital Space Concept”, John Tiller Software Technical Report, 10 Aug 2013.

[T11] “The Implementation of Rules of Engagement in the Analysis of Advanced Human Effects”, John Tiller Software Technical Report, 03 Jun 2014.

[T12] “A Summary of Algorithms and Analysis Associated with Risk Assessment and Tipping Points”, John Tiller Software Technical Report, 07 May 2011.

[T13] “A Human Strategy Template to Assist Wargaming AI”, John Tiller Software Technical Report, 12 Oct 2010.

[T14] “Application of Microplasma Lamps for Airborne Illumination, Optical Cloaking, and Collision Avoidance”, John Tiller Software Technical Report, 20 July 2012.

[T15] “High-Powered Electronic Warfare Attack”, John Tiller Software Technical Report, 06 July 2012.

[T16] “Modeling the Impact of Surface HPM Weaponry on Future Ground and Naval Air Defense”, John Tiller Software Technical Report, 27 Mar 2014.

[T17] “Modeling the Use of UCAV-Mounted HPM Weaponry in Future SEAD Missions”, John Tiller Software Technical Report, 12 Dec 2011.

Presentations

[PR1] Hussey, T. W., and Tiller. J., "Accounting for the Human Element in Air Operations Involving Emerging Weaponry", presented to Dr. Maybury, Chief Scientist of the Air Force, at the 2013 Global Horizons meeting, Wright-Patterson AFB, 20 Mar 2013.

[PR2] Tiller, J., Modern Air Power Tutorial, 80th MORSS (Military Operations Research Society Symposium), 11 June, 2012, US Air Force Academy, Colorado Springs, Colorado.

Book Articles

[BA1] "The Development and Application of the Real-Time Air Power Wargame Simulation Modern Air Power", Tiller, J., and Cavagnaro, C. E., submitted to *Zone of Control*, by Pat Harrigan and Matthew Kirschenbaum, to be published by MIT Press.

Contract Transitions

[TR1] "TAV Apple and Mobile Devices", Squadron Officer College, Maxwell AFB, Alabama, Aug 2014 – Aug 2015.

[TR2] "TAV Interface Requirements", Squadron Officer College, Maxwell AFB, Alabama, Sep 2012 – May 2013.

[TR3] "TAV Nuclear, Leadership, Critical Thinking, and Decision Making Enhancements, Squadron Officer College, Maxwell AFB, Alabama, Sep 2011 – Apr 2012.

[TR4] "Virtual Air and Space Operations Center (VAOC)", Squadron Officer College, Maxwell AFB, Alabama, Aug 2011 – Aug 2012.

[TR5] "Innovative Combat Simulation to Craft Tomorrow's UAV Operational Doctrine, Phase I STTR", Air Force Rome Research Lab, Rome, New York, May 2010 – Feb 2011.

[TR6] "Research into Future Naval Combat", Navy Strategic Studies Group, Newport, Rhode Island, May 2010 – Jun 2010.

[TR7] "Nuclear Enterprise Task – TAV Simulation", Squadron Officer College, Maxwell AFB, Alabama, Oct 2009 – Mar 2010.

Consultant Reports

[CR1] Ross, David, "Operation Hot Asphalt", 15 Nov 2013.

[CR2] Ross, David, "Operation Tar Baby", 15 Nov 2013.

Commercial Transitions

[CT1] "Panzer Campaigns: Kharkov '43", published by John Tiller Software, 03 Dec 2010.

[CT2] "Squad Battles: Modern War", published by John Tiller Software, 27 Dec 2010.

[CT3] "Panzer Campaigns: Tunisia '43", published by John Tiller Software, 11 Mar 2011.

[CT4] "Squad Battles: Falklands", published by John Tiller Software, 06 Aug 2011.

[CT5] "Panzer Campaigns: Moscow '42", published by John Tiller Software, 02 Nov 2012.

[CT6] "Panzer Battles: Battles of Kursk – Southern Flank", published by John Tiller Software, 28 Feb 2014.

[CT7] Modern Air Power app, published by John Tiller Software, for iPad, Kindle, and Android.

[CT8] 5 Panzer Campaigns apps, published by John Tiller Software, for iPad, Kindle, and Android.

[CT9] 2 Modern Campaigns apps, published by John Tiller Software, for iPad, Kindle, and Android.