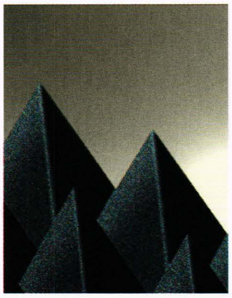


Force-Level Effectiveness Modeling for the Tomahawk Land Attack Cruise Missile

Steven M. Biemer

Force-level analysis of Tomahawk Land Attack Missile effectiveness and survivability in an operational context is a complex process requiring computer simulation models as analysis tools. Detailed one-on-one engagement simulations that model the performance of individual radars and surface-to-air missiles against a single Tomahawk are fundamental to this process. The analyst must integrate the results obtained from the models with information from other sources to develop an appropriate set of inputs to a force-level model simulating a multiaircraft strike against targets defended by a multicomponent defense system. After employing the force-level model, the analyst must study and interpret the results to obtain meaningful estimates of Tomahawk effectiveness and survivability. The Applied Physics Laboratory has a central role in these processes.

INTRODUCTION

The Applied Physics Laboratory has been the technical direction agent for the Tomahawk Weapon System (TWS) Program since its inception and is responsible for estimating and analyzing Tomahawk system effectiveness and providing those estimates to Navy decision makers. The Laboratory thus ensures that the TWS meets current and future operational requirements and assists the Navy in developing improvements for new variants of the weapon system.

Tomahawk effectiveness estimates must be developed within an operational context to take into account the synergistic effects associated with multiple missile strikes against targets defended by an Integrated Air Defense System (IADS). To include such effects, complex computer simulation models are used as analytical tools. Before the TWS can be examined at the operational level, the performance of individual IADS components, such as radars and Surface-to-Air Missiles (SAMs), against a single Tomahawk Land Attack Missile (TLAM) (Fig. 1) must be studied through detailed detectability and engageability analyses using engineering-level models. The analyst must incorporate the results obtained from these studies into an operational scenario by developing an appropriate set of inputs to the selected force-level models. These models are employed as part of an operational-level

Figure 1. Tomahawk Land Attack Missile in flight.

analysis. Finally, the results of the operational analysis are interpreted to obtain statistical estimates of TLAM effectiveness. Figure 2 is a schematic of this process, beginning with an examination of the study objectives (estimating TWS effectiveness) and extending through the analysis of the operational results. This article surveys the engineering and operational analyses and briefly describes the computer models listed in the figure under each process in a series of boxed inserts.

ENGINEERING-LEVEL ANALYSIS AND TOOLS

To estimate Tomahawk effectiveness at the engineering level (i.e., the subsystem or component level) requires detectability and engageability analyses. A detectability analysis focuses on a variety of surveillance systems (e.g., radar and passive detection systems), and an engageability analysis involves a wide range of SAMs, air-to-air missile systems, and gun systems. For the detectability analysis, several land-based radar modeling tools are available. One model is the Technical Radar Analysis Modeling System (TRAMS), which simulates a one-on-one encounter between an airborne vehicle (in this case a Tomahawk missile) and a single land-based radar (see the boxed insert on TRAMS).

The inputs for TRAMS include a functional description of the radar system, the radar cross section of the Tomahawk, and initial atmospheric conditions. Tomahawk trajectories are typically represented as a set of straight and level flight profiles, each at different altitudes, over flat terrain. If actual trajectories are available from the mission planning process described later in this article, they can be used over actual terrain.

Radar descriptions can be obtained through research in the APL Intelligence Library and visits to various intelligence agencies. Often, information that has been researched or generated previously can be used for current studies, thus saving much time in this one-on-one analysis.

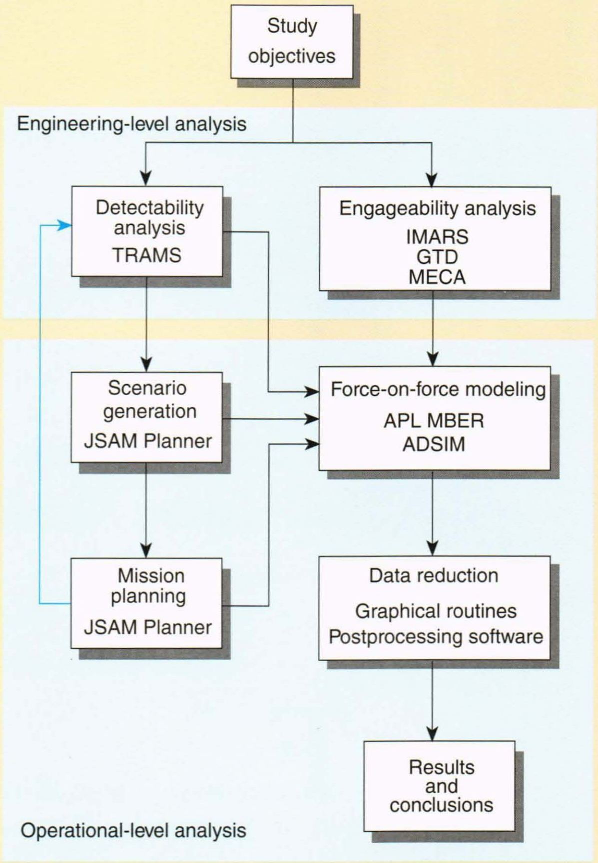


Figure 2. A model of the Tomahawk effectiveness analysis process. (TRAMS, IMARS, GTD, MECA, JSAM, and ADSSIM are detailed throughout the article.)

The output of TRAMS is horizontal and vertical plots of detection range for the radar against the Tomahawk. Figure 3 is a sample vertical plot from TRAMS. Radar detection contours (vertical and horizontal) representing the range at which the radar has a 50% probability of detection against the TLAM are used to define the initial geometry of the engagement in the engageability analysis as well as the detection capability of each radar in the operational-level analysis.[1]

Engageability analysis also requires detailed computer models to calculate important parameters and statistics. Two parameter sets are particularly important, as they tend to be major determinants in TWS effectiveness studies: the intercept envelope of each SAM type against a Tomahawk (consisting of the maximum SAM intercept range) and the single-shot probability of kill (SSP_k), given an intercept. These data are a function of intercept range, azimuth angle, Tomahawk altitude, and Tomahawk radar cross section; therefore, this analysis involves tens or even hundreds of cases representing the appropriate combinations of those factors.

TECHNICAL RADAR ANALYSIS MODELING SYSTEM (TRAMS)

The Technical Radar Analysis Modeling System is a collection of software tools dividable into two major sets. The first set includes analytical tools to examine seven aspects of the radar detection process using a high level of detail. These seven aspects are antenna design, waveform design, detection performance, tracking filter evaluation, filter design, radar-range equation evaluation, and Doppler processing. The seven tools are integrated so that the user may select one tool to design a component of the radar and incorporate that component within another tool. For example, the user may experiment with new antenna designs and examine those designs within the detection performance tool to calculate radar performance.

The second set of tools consists of three simulations that examine horizontal detection contours, vertical detection contours, and a flyby situation. The horizontal detection contour simulation evaluates the detection capability of a specified radar against a constant altitude target at selected horizontal cross ranges. The output is a graphical *xy* plot. The vertical detection contour simulation evaluates the detection capability against a constant cross-range target at selected altitudes. The output is an *xz* plot (see Fig. 3). Finally, the flyby simulation examines the detection performance of a radar against a single target flying along a user-entered trajectory, which is unconstrained in azimuth or altitude.

Within the three simulations, TRAMS models land-based pulse, pulse-Doppler, or continuous-wave radars operating against an airborne target. Each radar is defined through user-entered parameters; the user enters technical information, such as frequency and bandwidth, and the applicable operating modes or procedures. The target is defined by a target fluctuation-type (e.g., Swerling Type I), radar cross-sectional table, and, in the case of the flyby simulation, by a three-dimensional trajectory. The simulations use radar range equations to determine the radar performance. Included in the model are multipath calculations, clutter effects, attenuation, and detailed antenna representation. The flyby simulation incorporates the option to use either digitized terrain information from the Digital Terrain Elevation Database (DTED) provided by the Defense Mapping Agency or a simple spherical Earth model.

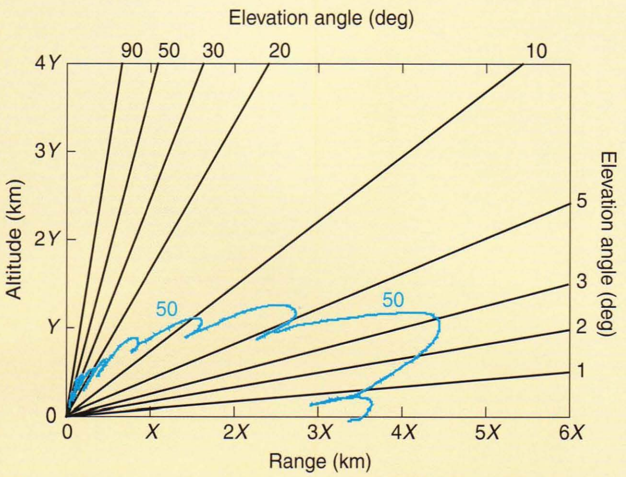


Figure 3. A vertical detection plot from TRAMS using a 50% probability of detection (*X* and *Y* denote any positive numbers).

Generating these data entails three steps, each requiring a separate computer model as follows:

1. The Integrated Missile and Radar Simulation (IMARS) is used to generate miss-distance statistics for each SAM type against the Tomahawk (see the boxed insert on IMARS). This simulation (located at APL) uses the detection information generated from the detectability analysis and stochastically models the missile flyout and engagement, resulting in an estimate of the SAM's closest point of approach (CPA) to the Tomahawk. Figure 4a schematically represents the CPA; Fig. 4b displays one output product of IMARS, a miss-distance contour, where the SAM system is located at the origin.
2. The CPA information is provided to the Naval Warfare Center/Weapons Division (NAWC/WD) at China Lake, California, where it is used to generate a fuzing point along the SAM trajectory. The fuzing point is the location along the trajectory at which the SAM fuze detects the Tomahawk and instructs the SAM warhead to detonate. A computer model based on the Geometric Theory of Diffraction (GTD) is used to determine this point (the model is referred to as the GTD model).
3. Finally, the fuzing point and the SAM trajectory are passed to another computer model at NAWC/WD known as the Modular Endgame Computer Algorithm (MECA). This simulation models the warhead blast pattern and the vulnerable areas of the Tomahawk. The trajectories of thousands of warhead fragments are calculated to derive an estimate of damage caused by the fragments that penetrate vulnerable areas. The aggregate results are examined to determine whether the Tomahawk was killed. Each encounter is repeated until statistical settling of average values occurs. The output of this simulation is the SSP_k for given pairs of Tomahawk and SAM trajectories. Parallel Tomahawk trajectories are examined, and P_k values are calculated for selected SAM intercept points along those trajectories. Figure 5a displays these TLAM trajectories and lists the calculated SSP_k values at different intercept points for a generic SAM. The points are color-coded according to SSP_k value. Figure 5b displays a sample SSP_k template that averages the P_k values over range and azimuth angles from the SAM to the intercept point.

Once the engineering-level analysis is complete, the analyst has obtained the following:

- Detection contours for various radars
- Engagement envelopes for selected SAM systems

- SSP_k templates for each SAM that are a function of intercept range, azimuth angle, and Tomahawk altitude.

This information will be used in an operational analysis, which is the other major phase of the force-level effectiveness and survivability analysis process.

OPERATIONAL-LEVEL ANALYSIS AND TOOLS

Scenario Generation

Before Tomahawk effectiveness can be examined at the operational level, the missile system must be studied within an operational scenario. Each scenario has five components as follows:

1. Tomahawk mission objectives
2. Strike asset descriptions (including Tomahawk and other strike weapons)
3. Target descriptions
4. Defensive order of battle (OOB) (the IADS)
5. Defensive system locations and tactics (i.e., their command and control structure)

Mission objectives are typically obtained from discussions with the Tomahawk Program Office (PMA-280), the office of the Chief of Naval Operations (OPNAV-N86), strike planners at the Naval Strike Warfare Center in Fallon, Nevada (NSWC/Fallon), and APL personnel. Targets that, when destroyed, will satisfy those objectives are typically identified by PMA-280, NSWC/Fallon, OPNAV, APL, and selected operational commands. If strike aircraft are involved, the Naval Air Systems Command (NAVAIR) will also participate in the mission definition and target selection process.

Unless the defensive OOB and site locations are already defined, the analyst must develop an appropriate database. Determining an OOB is accomplished through coordination with the applicable Defense Intelligence Agency (DIA) organizations for the time in question. Additionally, the Joint Chiefs of Staff have

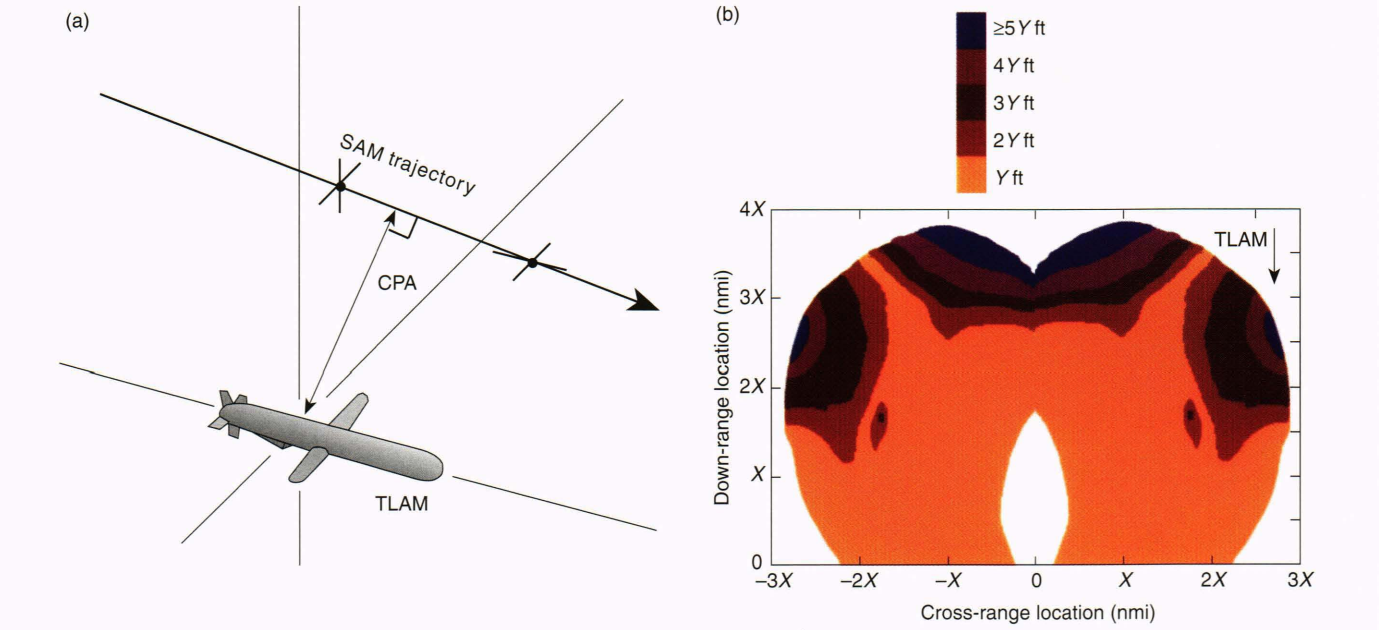


Figure 4. (a) Closest point of approach (CPA) of a SAM fired against a Tomahawk. (b) A contour plot from IMARS displaying the SAM's miss distance as a function of the down-range and cross-range location of the SAM's intercept point (X and Y denote any positive numbers).

INTEGRATED MISSILE AND RADAR SIMULATION (IMARS)

The Integrated Missile and Radar Simulation is a collection of simulations designed to model the Surface-to-Air Missile (SAM) engagement of an airborne target. Currently, versions of IMARS for the SA-5, SA-6, SA-8, SA-10, SA-11, and SA-12 land-based systems exist. The simulation models the tracking radar (detection is assumed to have occurred at model start), illuminator (for semiactive missile systems), communications links, and missile flyout and intercept. The radar model is based on radar-range equations and includes detailed clutter processing and multipath representation for low-altitude targets. SAMs are represented by a 6-degree-of-freedom model and are flown to the closest point of approach to the target. Missile lethality and target vulnerability are not modeled, nor are fuze and warhead models included. The output of the model is primarily miss-distance statistics (generated stochastically); missile engagement plots are also available.

The user is responsible for entering the three-dimensional target trajectory and missile radar operating modes. Additionally, the user may select site-specific terrain or a flat-Earth representation. If a site-specific terrain is selected, the Digital Terrain Elevation Database (DTED) is used.

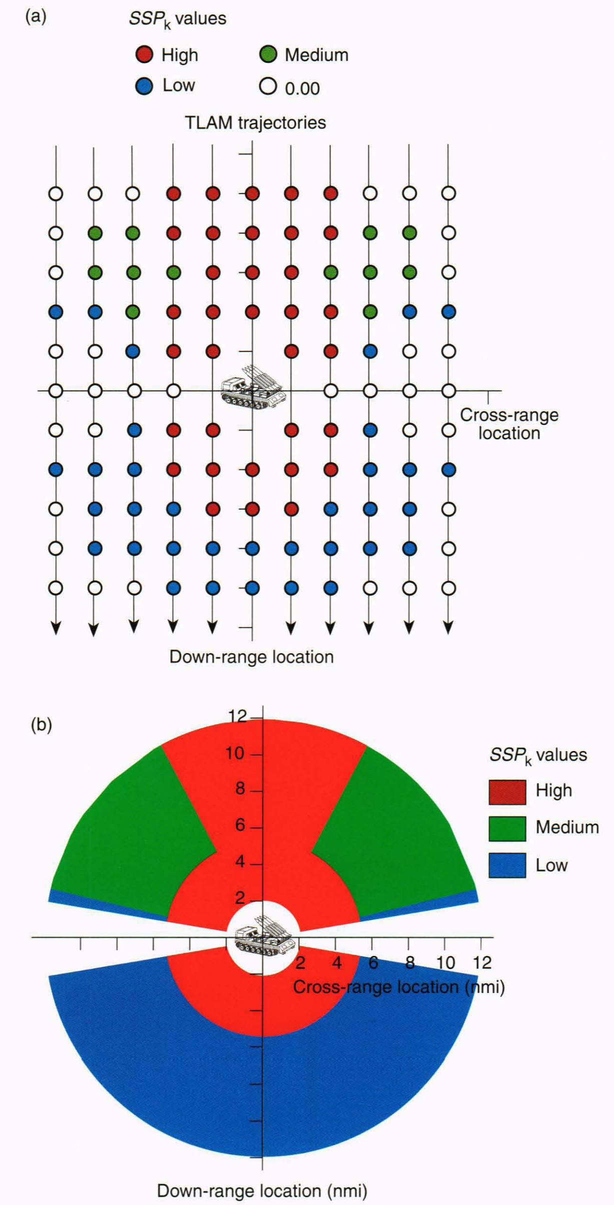


Figure 5. Modular Endgame Computer Algorithm (MECA) output. (a) Calculated MECA output SSP_k values for a sample SAM against a Tomahawk missile as a function of the down-range and cross-range locations of the SAM intercept point. (Each tick mark represents 2 nmi.) (b) A contour plot of SAM SSP_k values as a function of the down-range and cross-range locations of the SAM intercept point.

outlined seven Joint Planning Scenarios in the Defense Planning Guidance (DPG) that are recommended for use in Navy warfare appraisals and operational effectiveness studies (see the boxed insert on DPG scenarios).[2] These scenarios, which primarily consist of a defensive OOB and associated locations, have been approved by DIA and therefore provide foundational information for the development of an appropriate Tomahawk effectiveness analysis plan.

THE DEFENSE PLANNING GUIDANCE (DPG) SCENARIOS

The Joint Chiefs of Staff have outlined seven Joint Planning Scenarios in the DPG that are recommended for use in Navy warfare appraisals and operational effectiveness studies. These scenarios are collectively known as the DPG Scenarios and are used extensively throughout the Department of Defense. The seven scenarios represent the following situations:

1. **Major Regional Contingency—East:** A militarily aggressive country invades a neighboring country in its quest to become a dominant regional power in Southwest Asia.
2. **Major Regional Contingency—West:** A militarily strong country in Southeast Asia invades a neighboring country with the objective of destroying its current political system.
3. **Major Regional Contingency—Concurrent:** A combined major regional contingency occurs in the East and West separated by 45 days.
4. **Major Regional Contingency—Europe:** A major regional power makes an expansionist thrust into a neighboring country and is opposed by a post–Cold War NATO.
5. **Lesser Regional Contingency—Near:** A destabilizing revolution that may result in the taking of many American and third-nation hostages threatens U.S. interests in the Western Hemisphere.
6. **Lesser Regional Contingency—Far:** The aftermath of a destabilizing insurgency far from the United States poses a threat to U.S. interests and citizens.
7. **Reconstitution:** A superpower emerges to challenge the United States militarily. This scenario represents the period in which the United States must reconstitute its forces to deter aggression.

The DPG Scenarios are each two to three pages long and contain few technical details. The Space and Naval Warfare Systems Command (SPAWAR 31) and the Naval Air Warfare Center/Weapons Division have provided technical details of the defensive orders of battle and laydown for each of the military scenarios listed above (all but the Reconstitution scenario). These documents, which are continually updated, contain detailed information that provides the analyst with a foundation for examining the operational effectiveness of the Tomahawk Weapon System. The analyst is responsible for tailoring the scenario to ensure relevance without violating the basic assumptions outlined in the documents.

Defensive site locations given in the DPG scenarios may need to be modified or enhanced by analyzing the IADS components and the Command and Control (C^2) structure of the Tomahawk-specific scenario. In examining the IADS, terrain masking is a major issue for defensive system placement when defending against low-altitude cruise missiles (such as Tomahawk). To address terrain masking effects on defensive system placement, a software tool that uses digitized terrain information from the Digital Terrain Elevation Database (DTED), provided by the Defense Mapping Agency, is employed. This tool is known as the Joint Strike Analysis Model (JSAM) Planner (JSAM is a simulation currently under development that will use JSAM

Planner; however, JSAM Planner can be used independently).

Figure 6 is an example of JSAM Planner output and displays a sample defensive site placement scheme for four radars to provide radar coverage of a coastal region. The shaded portion represents those areas where the radar has a line of sight to a low-altitude target, although it still may not be able to detect or track the target owing to other factors. It is evident that several areas are masked from the line-of-sight view of the four radars; for example, the valley in the center receives only spotty coverage from the center radar. Figure 7 shows a more optimal placement of the four radars to ensure proper coverage of the coast. When the two center radars are moved closer to the water, the local IADS can provide continuous coverage of the coastal region. This type of coverage analysis is used to ensure that the defensive placement and structure will present an operationally realistic threat to the Tomahawk strike.

Offensive Mission Planning

Mission planning is divided into two steps: determining the number and type of Tomahawk missiles to assign to each target (this step is called weaponeering) and developing TLAM routes. First one must determine the weapon's probability of damage against specific target types, which is generally the product of the weapon's probability of hitting the target (P_H) and the probability of damaging the target given a hit ($P_{D|H}$). For Tomahawk, this calculation is a function of missile accuracy, expressed as circular error probable (CEP), the size and characteristics of the missile's warhead, and the target characteristics (primarily its ability to withstand blast and fragmentation damage).

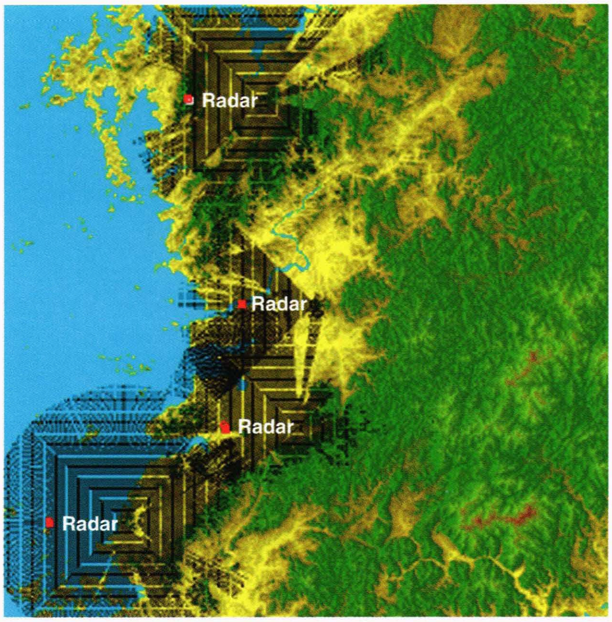


Figure 6. Defensive site placement scheme for four radars from JSAM Planner output. The shaded areas represent the line of sight for four early warning radars defending a coastline overlaid on a DTED map.

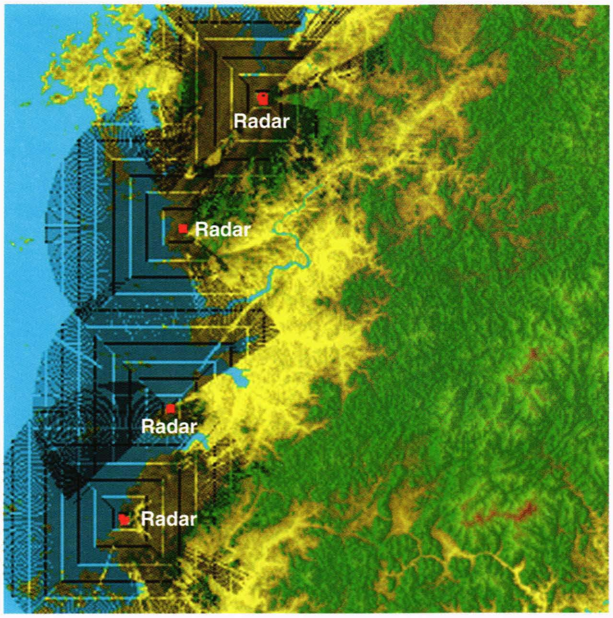


Figure 7. A more optimal placement of four radars defending the same coast as in Fig. 6.

For example, against a specified building, a Tomahawk cruise missile may have a 0.7 probability that it will cause sufficient damage to satisfy a preselected damage criterion (P_D). These criteria are defined in the Joint Munitions Effectiveness Manuals for many weapon/target pairs. Against a very small building, the Tomahawk P_D may be small owing to the low probability of hitting the target as opposed to the ability to destroy it if hit (e.g., if P_H is 0.1 and $P_{D|H}$ is 0.9, the P_D would be 0.09). Similarly, against a very large building, the Tomahawk P_D may be small because the missile's warhead is not sufficient to destroy the building even though the probability of hitting a piece of the building and damaging it is high.

When more than one missile hits a target, a cumulative P_D is calculated by

$$\text{Cumulative } P_D = 1 - (1 - \text{single shot } P_D)^N ,$$

where N = the number of Tomahawk hits achieved on the target.

For analysis purposes, a required cumulative P_D threshold is determined to define when a target can be considered destroyed. Thus, to declare a target destroyed, the cumulative P_D must exceed the predetermined threshold. If the single-shot Tomahawk P_D is greater than this threshold, only one missile is required to hit the target before it will be declared destroyed. Otherwise, additional missiles must be assigned.

Once the missile assignments have been established, the flight routes must be developed. The flight-route generation process can be thought of as an optimization problem, since various constraints limit where a Tomahawk route can be placed. These constraints include the following:

- Navigation constraints
- Capabilities and locations of threats
- Time of arrival constraints
- Launcher constraints
- Target approach route feasibility

To determine the constraints posed by the threats, the DTED tool (described earlier) is used. This software tool is not an automated route generator; rather, it is a display tool with which the analyst can evaluate candidate TLAM routes. The tool can display an overhead view of the candidate route and the various threat sectors perturbed by local terrain. In addition, a vertical profile of the route and the terrain directly below can be displayed. The analyst can then modify the altitude of the TLAM route manually to reflect operational knowledge of Tomahawk terrain-following capabilities.

The analyst can rely on a naval operational planner to assist in developing TLAM routes. Ideally, the routes should be planned by the operational Cruise Missile Support Activities (CMSA), located in Norfolk, Virginia, and San Diego, California, since these activities plan operational TLAM routes for the Navy. Security constraints, limited knowledge of future weapon system characteristics, and tasking priorities, however, typically preclude using a CMSA to plan routes for Tomahawk effectiveness studies. Other sources for operational planning include NSWC/Fallon, the Washington, D.C., CMSA (a training/testing facility), the Naval Surface Warfare Center in Dahlgren, Virginia, and various personnel within APL with expertise in Tomahawk mission planning. Regardless of who plans the routes, they must consist of a series of turn waypoints and altitude action points between the launch point and the target.

Since TLAM mission plans may not be sufficient for the operational analysis, a TLAM trajectory may need to be developed. This trajectory would include detailed altitude information along the route, navigation update points, and actual latitude/longitude/time locations. Depending on the level of fidelity required, the trajectory can be generated in a variety of ways. If high fidelity in the trajectory is not required, the trajectories can be derived manually from the routes on the basis of missile climb/dive rates. If more fidelity is required, a 6-degree-of-freedom simulation can be used to generate trajectories, given the information about the planned route.

Once the Tomahawk weaponeering data and flight trajectories have been produced, the analyst is ready to start the operational analysis.

Force-on-Force Simulations

All of the necessary data are now available to perform a force-on-force analysis. If survivability information is known or assumed and the Tomahawk missile strike is against strategic, nondefended targets, a spreadsheet may be used to determine the probability of destroying individual targets, from which other information can be calculated. In most cases, however, survivability information in a many-on-many context is not known because multiple TLAMs in a strike cause synergistic effects in overcoming an IADS. Multiple missiles can confuse or even saturate single IADS components, contributing to an overall degradation of performance. Only a many-on-many analysis using a sophisticated simulation will be able to represent this reality.

The Laboratory uses two force-on-force simulations: APL MBER and ADSIM. The former is an APL-enhanced version of the Multiple Battlefield Engagements and Reactions Model (see the boxed insert on APL MBER). This simulation models a multiple Tomahawk and aircraft strike against targets defended by a ground-based IADS.[2] The Air Defense Simulation (ADSIM) is an APL-developed simulation that models a Tomahawk-only strike against targets defended by an airborne IADS.[3] Output from both simulations can be integrated to represent the strike against the airborne and ground-based portions of the IADS whenever the two types of engagements occur in sequence. When they occur concurrently, an iterative approach is used. Both models are executed and the results incorporated into the other at selected times to represent the necessary interaction.

Outputs and Measures of Effectiveness

Both graphical and tabular output are provided by APL MBER. The graphical output is obtained from a standard output file containing event records used by a graphics program to animate the events. With this tool, the user can step through a single run of the simulation. Flight paths of each Tomahawk are drawn, as well as the locations of SAM sites and targets. When a SAM engages a TLAM, an engagement line is drawn between the SAM and the current position of the TLAM. Symbols represent events such as a TLAM kill by a SAM (a red circle), a SAM miss (a red X), and a target hit by a TLAM (a red box). Finally, the output can be overlaid on the DTED of the area. Figure 8 displays sample graphical output overlaid on a DTED map of the area.

The Air Defense Simulation can also produce graphical and tabular output. The graphical display is similar

APL MULTIPLE BATTLEFIELD ENGAGEMENTS AND REACTIONS MODEL (APL MBER)

The APL MBER is a stochastic operational-level simulation that models an airborne strike against targets defended by a ground-based Integrated Air Defense System (IADS). The strike package can include cruise missiles, strike aircraft carrying weapons, antiradiation missiles, support jamming aircraft, loitering air vehicles (such as unmanned aerial vehicles), and airborne decoys. Since APL MBER defines air vehicles generically using input parameters, any airborne strike aircraft or missile can be represented. Furthermore, antiradiation missiles and jamming platforms can be defined to react to defensive stimuli (i.e., RF transmissions). This simulation represents targets as a point mass at a single location.

Defensively, APL MBER models individual components of the IADS such as the following:

- Early warning radars
- SAM systems, including acquisition, tracking and illuminating radars, as well as launchers, reload capability, and missile inventories
- Gun systems, including RF and electro-optical acquisition and tracking systems
- The C^2 structure that defines the coordination among the components

Part of the C^2 structure includes command centers that control selected IADS components. Each component is defined generically by input parameters; thus, any defensive system can be represented. Furthermore, the C^2 structure is user-definable and can represent a local air defense system. This structure allows the user to define target prioritization schemes, target assignment logic, track file capacities at different command levels, and reaction delay times.

Functionally, the IADS initiates tracks of penetrating strike aircraft through RF and electro-optical sensors (possibly in a jamming environment) and communicates those tracks to a command center, where the track is evaluated for action. Following the evaluation, the track is assigned to an IADS component (typically a SAM battery), and an engagement scheduled. The engagement is evaluated stochastically; if the result is a kill, the battery initiates a reload sequence (if required) and becomes available for another assignment. If the result is a miss, the battery checks whether it can engage again and, if so, schedules another engagement.

The strike aircraft or missile can be assigned a component of the IADS as a target. If the aircraft or missile is successful at reaching its target, a stochastic evaluation is performed. If the target is destroyed, the IADS component is removed from the IADS structure and is unavailable for use. If a command center is destroyed, the subordinate components become independent and free to acquire and engage targets at will (thus, they lose the information and coordination available from the C^2 structure).

Tabular output from the simulation is user selectable and can include up to all possible events recorded by the program. Thus, the analyst can obtain profuse data from a single execution. Postprocessing programs are available to reduce the output by filtering appropriate data and generating distributions for selected measures of effectiveness (MOEs) by integrating the results from multiple iterations. Any event can be selected as an MOE.

The APL MBER simulation was developed by Kamak Research Corporation and has been used for various Navy and Air Force operational analyses for over 10 years. The Laboratory acquired the source code from Kamak in 1988 via a permanent lease agreement and has significantly enhanced the original version, renaming the simulation APL MBER to distinguish it from the MBER simulation, which still exists at Kamak.

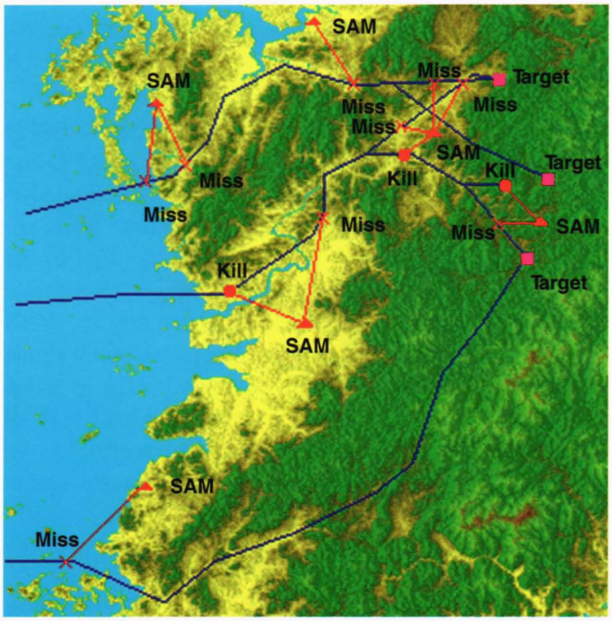


Figure 8. Sample APL MBER output overlaid on a DTED map.

to that of APL MBER except that enemy aircraft and their air-to-air missile engagements are displayed as well as enemy airfields and early warning radars with TLAM detection range rings.

Although the force-on-force models can provide output for many parameters, top-level measures of effectiveness (MOEs) must be chosen that address the study objective. In short, these measures are what the analyst will use to define effectiveness. From among the many possible measures, the following are several candidates:

- Probability of destroying a percentage of a target set
- Probability of arriving at a target
- Probability of survival
- Probability of striking a target within a certain time window
- Minimum number of TLAMs required to damage a selected target set
- Number of TLAMs reaching their target
- Number of aircraft saved by using TLAMs

- Number of aircraft sorties required against a target set when TLAMs are present
- Number of aircraft sorties saved by using TLAMs

In addition, secondary measures may need to be determined by decomposing a primary measure into its components. For instance, a measure like "number of TLAMs required" could consist of an equation involving two other measures:

$$\mathrm{TLAM}_{\mathrm{required}} = \mathrm{Total\ TLAM}_{\mathrm{launched}} - \mathrm{TLAM}_{\mathrm{reliability\ failures}} - \mathrm{TLAM}_{\mathrm{attrited}} .$$

In this case, the number of reliability failures and of TLAM attrited are two lower-level measures. The first can be assumed on the basis of TLAM specification values or testing experience; the second is calculated by APL MBER. By successively decomposing MOEs, the analyst eventually arrives at measures that can be calculated mathematically, estimated by simulation, assumed, or parameterized. At that point, the decomposition is sufficient. In some instances, no decomposition is needed.

Analysis of the Results

Once the input databases have been defined, the analyst executes the stochastic models and collects statistics on the selected MOEs. When this baseline analysis is complete, the analyst has the option of performing three additional types of analysis that may (and often do) provide vital information in understanding the simulation results.[4] The first type of analysis is parameterization, which is the process of selecting a set of parameters (usually just one) and varying their values to calculate the boundary conditions on a selected MOE. Parameterization is typically performed when the value of the parameter is unknown or known with a level of uncertainty. It is quite useful in examining "worst-case" or "best-case" scenarios as well.

The second approach is sensitivity analysis. The process is the same as parameterization, but the purpose is different. In this type of analysis, the analyst calculates the selected MOE for varying values of a single input parameter to determine how sensitive the resulting MOE value is in relation to the varying parameter. If the resultant MOE value fluctuates greatly with small perturbations to the input parameter, the MOE is said to be sensitive to the input parameter; otherwise, it is insensitive. This type of analysis can assist in determining which inputs account for their observed values.

The third method, called case studies, is very common in Tomahawk effectiveness studies and entails developing and examining several cases with different assumptions independently. The resulting MOE values are compared, and conclusions are drawn. For example, the number of TLAMs participating in a strike against a common target set would represent a case study. Suppose the MOE is the probability that 80% of a selected target set was destroyed. Figure 9 presents a sample case study result for this situation. Notice that the lowest quantity is entirely insufficient to destroy 80% of the target set. Also observe that, at larger quantities, the marginal increase in probability is reduced considerably. The most cost-effective quantity would therefore be either the center value or, possibly, the fourth quantity. Adding missiles would be cost-ineffective (or even wasteful).

Regardless of the type of analysis, the analyst must understand that the output of any stochastic operational-level simulation is statistics, not truth. Stochastic simulations produce probability distributions of selected MOEs. It is up to the analyst to determine what those distributions mean.

It is tempting for the analyst to calculate mean values for each MOE and use those values as the answer, but this approach can be deceptive. Assuming the output distributions are normally distributed (typically they are when a sufficient number of iterations are run—but not always), confidence intervals can be used when comparing and displaying the same MOE for different cases. A common statistical test to determine whether two mean values are equal when the variances are unknown (but equal) is the Student's-t test with $n_1 + n_2 - 2$ degrees of freedom, where n_1 and n_2 are the sample sizes of the two cases.[5]

Figure 10 is a sample plot of Tomahawk survivability versus the number of Tomahawk missiles employed. Although the mean values differ, the 90% confidence intervals suggest that the values are equivalent for the three larger quantities of TLAMs. In fact, the equality conclusion can be substantiated after statistical tests are applied to these values.

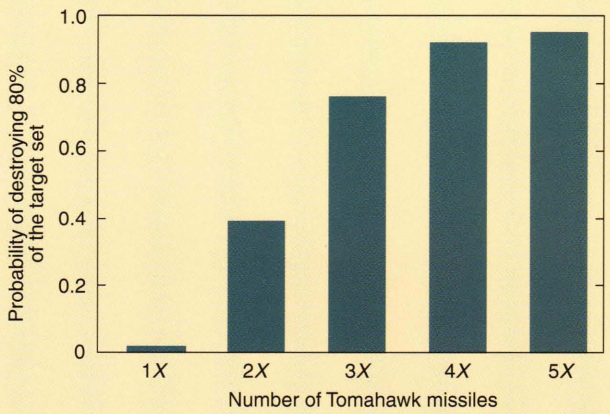


Figure 9. Sample case study result showing the probability of destroying 80% of a sample target set (*X* denotes any positive number).

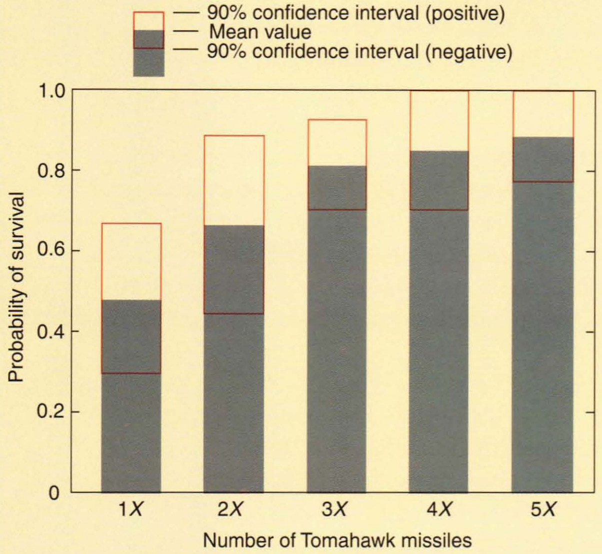


Figure 10. Aggregated probability of survival statistics for a Tomahawk strike using the quantities listed in a sample scenario (*X* denotes any positive number).

Once the statistical values are understood, conclusions can be drawn on the basis of the input data, scenario assumptions, and force-on-force model limitations. This process is more of an art than a science. Although observations can easily be made from graphical presentations of the data, the meaning of the data in relation to the study objectives may not be readily apparent. Experience is required before the analyst can quickly identify and present the important conclusions.

The final step in the Tomahawk effectiveness analysis process involves presenting the results in a format understandable to the nonmathematician and integrating documentation collected throughout the process to formulate a report.

SUMMARY

Estimating Tomahawk effectiveness within an operational scenario requires the integration of results from several analyses. Engineering-level simulations examining the detectability, engageability, and vulnerability of the Tomahawk cruise missile against components of an IADS are used to provide inputs to mission planning and force-level models that estimate TLAM effectiveness in the context of an operational scenario. Through the effective application of the process described in this article, APL can ensure that the TWS meets current and future operational requirements and provide the Navy with valuable effectiveness information in developing improvements for new variants of the weapon system.

REFERENCES

[1] Mitchell, R. L., and O'Donnell, P. A., *Technical Radar Analysis and Modeling System*, Mark Resources, Inc., Santa Monica, CA (1988).

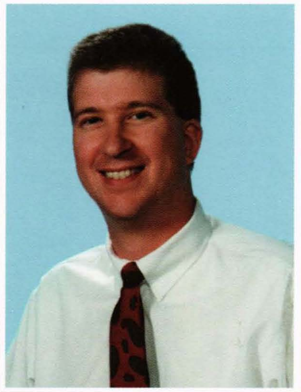
[2] *Multiple Battlefield Engagements and Reactions Model User's Guide*, TR-12-87, Kamak Research Corp., San Diego, CA (Sep 1987).

[3] *ADSIM Program Description and Usage Documentation*, JHU/APL BAS-88-094 (Dec 1988).

[4] Law, A. M., and Kelton, D. W., *Simulation Modeling and Analysis*, 2nd Ed., McGraw-Hill, New York, pp. 522–601 (1991).

[5] Dunn, O. J., and Clark, A. V., *Applied Statistics: Analysis of Variance and Regression*, 2nd Ed., John Wiley & Sons, New York, pp. 37–51 (1987).

THE AUTHOR



STEVEN M. BIEMER received his B.E.S. in mathematical sciences and M.S. in computer science from The Johns Hopkins University in 1985 and 1990, respectively, and is currently pursuing an M.S. in technical management. Since joining APL in 1985, Mr. Biemer has worked in the Strike Warfare Group of the Naval Warfare Analysis Department analyzing cruise missile survivability and effectiveness and participating in OPNAV-sponsored analytical studies that have explored future surface combatant concepts. Most recently he has served as the lead strike analyst for the DDG-51 Flight IIA variant study. In 1991, Mr. Biemer was appointed Supervisor of the Systems Analysis Section, recently renamed the Air Warfare Section. Currently, he is examining electronic warfare effectiveness for the F/A-18 strike fighter.