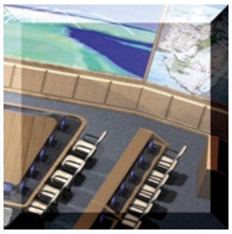

Air-Directed Surface-to-Air Missile Study Methodology

H. Todd Kauderer

During June 1995 through September 1998, APL conducted a series of Warfare Analysis Laboratory Exercises (WALEXs) in support of the Naval Air Systems Command. The goal of these exercises was to examine a concept then known as the Air-Directed Surface-to-Air Missile (ADSAM) System in support of Navy Overland Cruise Missile Defense. A team of analysts and engineers from APL and elsewhere was assembled to develop a high-fidelity, physics-based engineering modeling process suitable for understanding and assessing the performance of both individual systems and a "system of systems." Results of the initial ADSAM Study effort served as the basis for a series of WALEXs involving senior Flag and General Officers and were subsequently presented to the (then) Under Secretary of Defense for Acquisition and Technology. (Keywords: ADSAM, Cruise missiles, Land Attack Cruise Missile Defense, Modeling and simulation, Overland Cruise Missile Defense.)

INTRODUCTION

In June 1995 the Naval Air Systems Command (NAVAIR) asked APL to examine the Air-Directed Surface-to-Air Missile (ADSAM) System concept for their Overland Cruise Missile Defense (OCMD) doctrine. NAVAIR was concerned that a number of important air defense–related decisions were being made on the basis of results from medium- to low-fidelity models. They wanted APL to (1) analyze and assess air defense systems and concepts using the most detailed and highest-fidelity models, (2) examine the military capabilities and utility of the ADSAM concept using the results of this high-fidelity modeling, and (3) if warranted, transition the concept to an engineering-based project.

The ADSAM Study explored and demonstrated the technical and operational viability of the concept by

- Developing an analytical methodology that tied together a series of previously distinct, "stovepiped" high-fidelity engineering models into an integrated system that allowed the detailed analysis of a "system of systems"
- Modeling, analyzing, and assessing the performance limitations of component systems and the overall system using these high-fidelity system models
- Applying the APL Warfare Analysis Laboratory (WAL) Exercise (WALEX) approach to examine the operational capability and viability of the proposed system
- Using the WAL, its display and visualization capabilities, and a seminar approach to convey analytical results and an operational understanding to high-level decision makers

BACKGROUND

Concept

The ADSAM concept was developed by the Navy in response to the increased threat of enemy Land-Attack Cruise Missiles. The major limitation to naval OCMD is the inability of current shipboard radar to see low-flying targets far inland owing to the Earth's curvature and terrain blockage. Unlike ballistic missiles, which fly in a predictable trajectory, Land-Attack Cruise Missiles can also change course, making identification of their intended targets as uncertain as with engagement of manned aircraft. The ADSAM concept uses airborne sensors to detect, track, and possibly illuminate these targets, passing sensor data via Cooperative Engagement Capability (CEC) data links to Aegis ships off the coast. This allows ships to engage enemy missiles even if the targets go undetected by their own onboard sensors (Fig. 1).

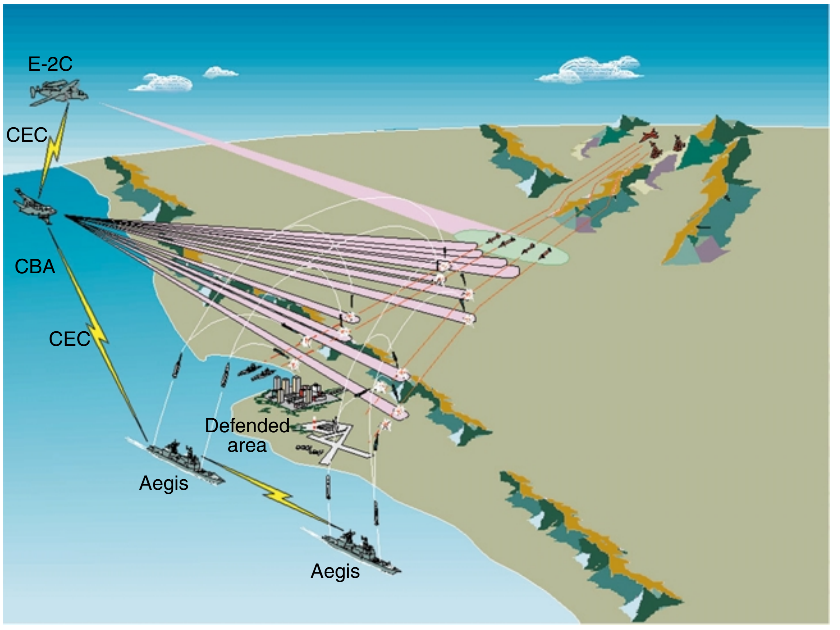

Figure 1. The goal of the ADSAM concept is to extend Fleet Area Air Defense overland to defend ports, airfields, and U.S. and Allied expeditionary forces from cruise missile and aircraft attack. (CEC = Cooperative Engagement Capability, CBA = carrier-base aircraft used here for fire control.)

Methodology

The various levels of modeling fidelity used in the analytical approach described here can be likened to a pyramid (Fig. 2). Knowing where the analyst is along the analysis hierarchy is critical to understanding the level of system fidelity that the process represents. At the top of the pyramid are campaign-level models that typify factors encompassing thousands of personnel and systems over days, weeks, or months. Of necessity, these representations are highly aggregated and are limited in their ability to accurately model the detailed capabilities of individual systems. The next two levels—force-on-force and unit/systems modeling—exemplify the capabilities of the systems. The bottom tier of the pyramid, sometimes called the "fundamental" or "engineering" level, represents a higher level of fidelity for individual components of the systems and for the system of systems. The ADSAM methodology resides at the bottom of the fundamental level, the foundation of the pyramid.

The ADSAM Study Team modeled the detect/control/engage process in OCMD at the fundamental level using the highest-fidelity model of each component available within the defense community. The Naval Research Laboratory (NRL), for example, provided the Navy Airborne Surveillance Model. As part of the ADSAM methodology, all models were operated by their owners to ensure that their design, assumptions, limitations, and operations were thoroughly understood (Fig. 3). Each model used also had Program Office accreditation for that component. This practice established the credibility and acceptance of the output.

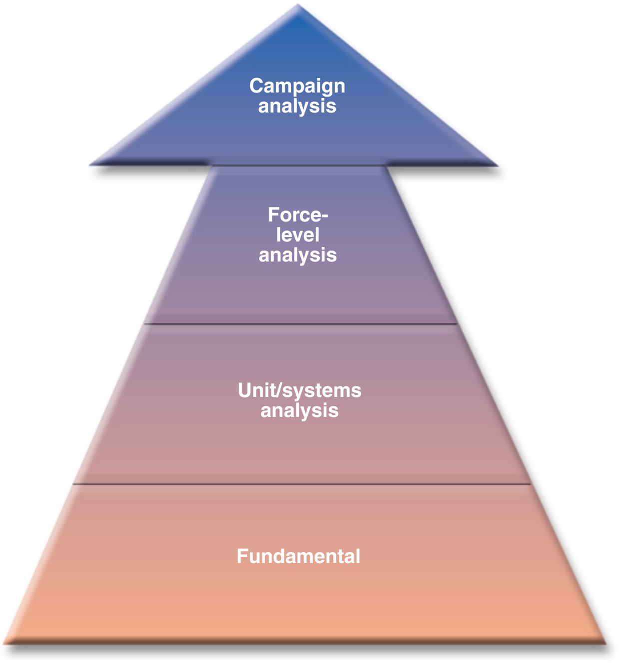

Figure 2. Analysis hierarchy. Recognizing the analyst's position within the hierarchy is critical to an understanding of the level of system fidelity that the process represents. The ADSAM methodology resides at the bottom of the lowest level of the pyramid.

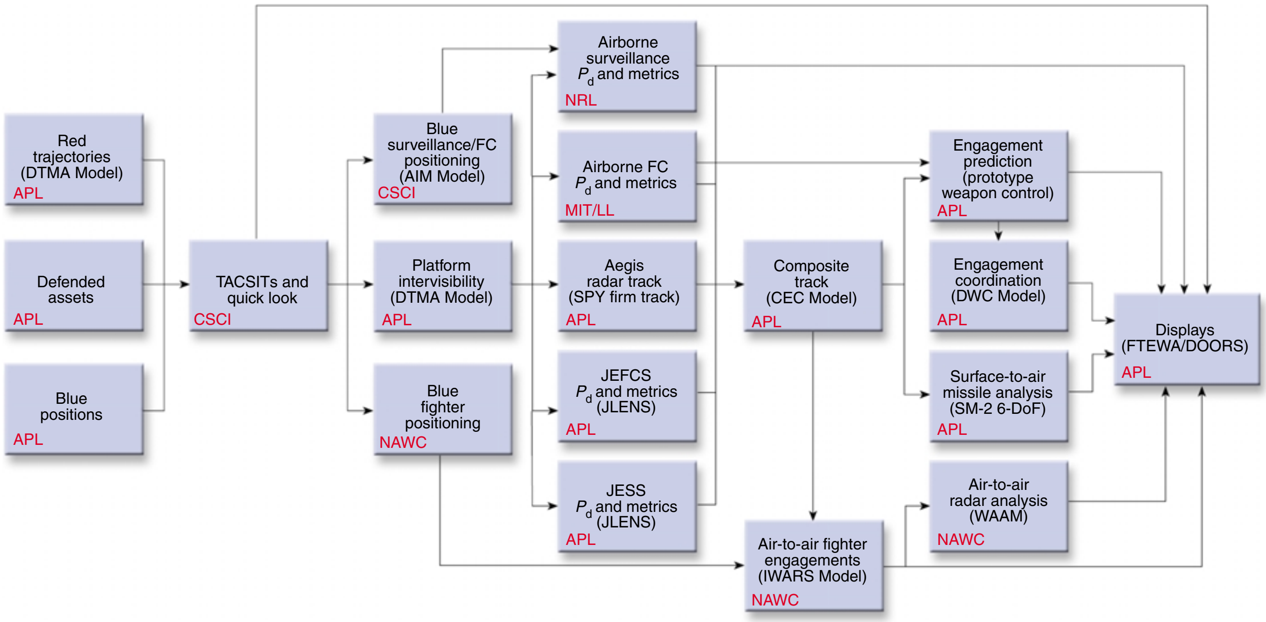

Figure 3. ADSAM 1998 analysis methodology. This simplified chart represents the data flow of high-fidelity models spread throughout the country. Model locations are indicated in red. (AIM = Air Intercept Missile, CEC = Cooperative Engagement Capability, DoF = degree of freedom, DOORS = Distributed Object-Oriented Real-Time System, DTMA = Digital Terrain Mapping Application, DWC = Distributed Weapons Coordination, FC = fire control, FTEWA = Force Threat Evaluation and Weapons Assignment System, IWARS = Integrated Warfare Architectures, JEFCS = Joint Elevated FC System, JESS = Joint Elevated Surveillance Sensor, JLENS = Joint Land-based Elevated Netted Sensor, MIT/LL = Massachusetts Institute of Technology Lincoln Labs, NAWC = Naval Air Warfare Center, P_d = probability of detection, TACSITs = tactical situations, WAAM = Weapons Analysis and Assessment Model; JEFCS and JESS comprise the APL representation of JLENS.)

Results from each location were integrated through the development of standard formats for data exchange. Although previous uses of many of the models generally involved stand-alone processing, outputs of each model in ADSAM were modified to be compatible with inputs of the next model in the series. The physical data flow itself was performed via floppy disk and e-mail.

Using this modeling architecture, multiple scenarios from different theaters were developed and analyzed. To examine key system interactions, the 40- to 45-min flight time of each enemy missile was divided into 0.25-s increments (yielding approximately 8 to 9000 points of measurement for each representation of an enemy missile trajectory) to examine all factors important to the problem. Missile flight paths were modeled by APL staff knowledgeable about advanced cruise missile systems. Since sensors would have to detect and track threats from continuously changing aspects, a full aspect-dependent representation of the threats (Fig. 4) was developed in conjunction with the intelligence community. This allowed a much greater validity in threat representation than possible with a two-dimensional representation typical of higher-level models.

Surveillance radar modeling performed by NRL and MIT/LL system engineers and analysts provided inputs to the fire control modeling analysis. The fire control process was the most complex. Seventeen critical factors or events had to occur successfully, in the right sequence, to achieve intercept (see, e.g., Fig. 5). If any one or more of the factors failed, then the attempted intercept would fail (miss).

To make these extremely complex data more easily understood, the Force Threat Evaluation and Weapons

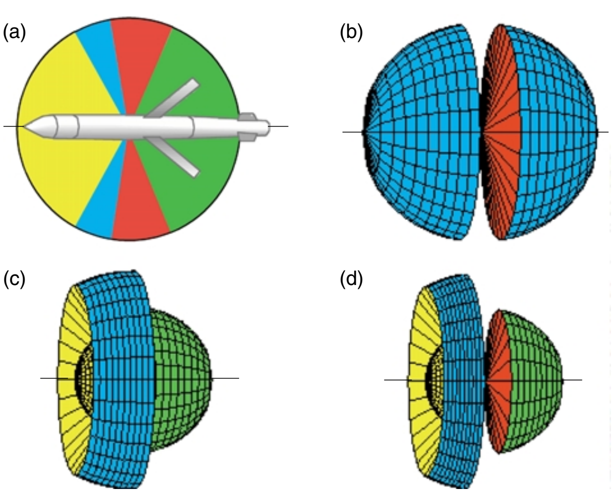

Figure 4. Aspect-dependent differences must be reflected in the representation of the target being modeled when analyzing the view from surface platforms looking up at a target, aircraft looking across the target, or interceptors diving on the target. (a) Two-dimensional combined effect (low fidelity), (b) clutter Doppler notch, (c) radar cross section, and (d) radar cross section with clutter Doppler notch.

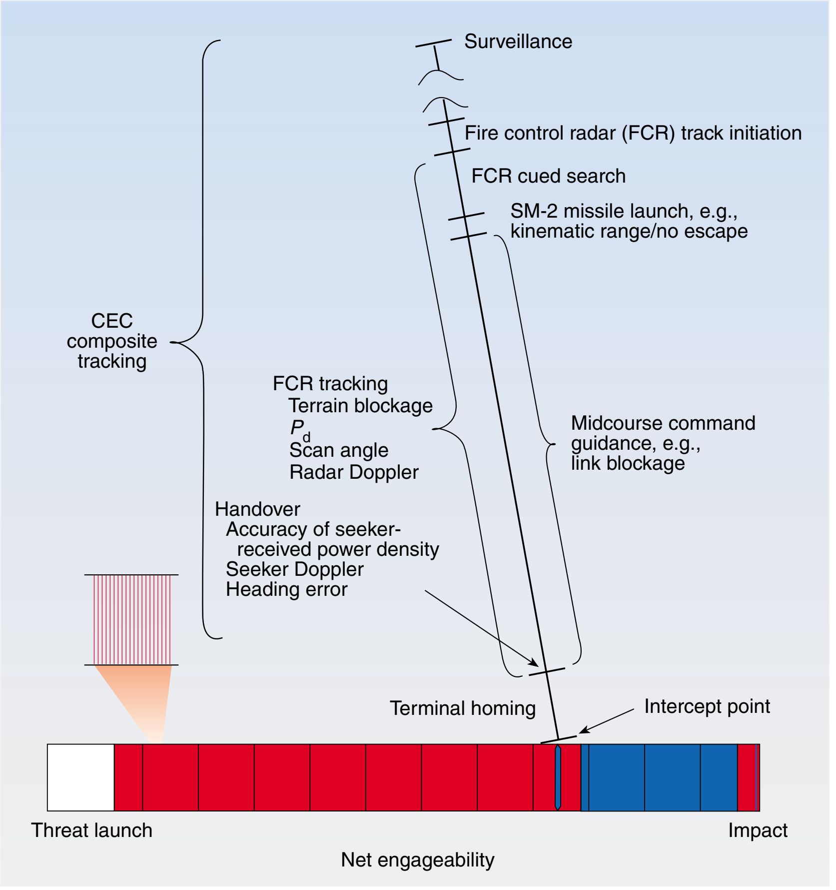

Figure 5. Engageability factors. Once surveillance tracking has transitioned to the fire control process, all of the factors shown must meet success criteria, in the right sequence, to allow target intercept. ADSAM modeled each process every 0.25 s through the 40- to 45-min flight time of the target. If at least one factor (component) failed, then the result was displayed as a single vertical red line. Success was displayed by blue lines. A typical enemy flight would be represented by about 8 to 9000 lines.

Assignment (FTEWA) System was applied for display data during WALEXs. The system uses model data to drive dynamic three-dimensional displays, presenting the modeled results to audiences in time-controllable pictures of a situation at 1-s increments. The FTEWA System is currently being installed in the Fleet.

THE ADSAM STUDY METHODOLOGY, 1995–1997

The first ADSAM Study began in the summer of 1995. Its initial objectives were principally to study concept design and validation. Could a true system-of-systems engineering-level analysis be conducted using previously stand-alone models of each component? Could results be understood and accepted by a wide variety of audiences, from engineers to operators, including representatives from different services? Could highly complex OCMD interactions and requirements be displayed so that all observers would understand the results?

Several representative advanced systems concepts were modeled including an advanced E-2C Hawkeye Navy airborne surveillance aircraft; a concept for an improved large, land-based airborne surveillance aircraft; an airborne fire control illuminator supporting the needs of naval semi-active guided interceptors; and a single Aegis ship as the firing platform. The CEC process was assumed to allow connectivity of the required fire control data. During the early ADSAM studies, engageability was assessed using postflight analyses in which an intercept point was computed for each 0.25 s of target trajectory. The engagement process was then worked backwards to see if all necessary factors would have met requirements, in the right sequence, for a successful engagement. Results were then displayed, system component by component, over the timeline of the enemy trajectory, and factors enabling and limiting the system of systems were highlighted (Fig. 6).

Over the next 3 years, systems were added to and deleted from the study as required to satisfy each year's specific goals. In 1996, Navy-unique systems were examined in greater detail. In 1997, under the sponsorship of the J8 section of the Joint Staff, the first true examination was conducted of a scenario employing Joint systems such as the Air Force AWACS aircraft, the Army Patriot SAM systems, and Navy systems. Modular capabilities of the methodology provided great flexibility while maintaining the credibility of the engineering-level analysis.

The WALEX process was used successfully to present objectives and complex study results to a wide variety of participants. Attendees were then given the opportunity to provide their responses, express their concerns, and offer guidance to the sponsors. Not all issues were immediately resolved in the WALEXs, but direction was provided where additional study and requirements definition were needed.

Also during this period, the requirement to replace the assumption of CEC capability with a comparable high-fidelity model of the CEC composite track function led to the development of a model that could take inputs from other high-fidelity models. In many ways this was the most complex effort developed for the

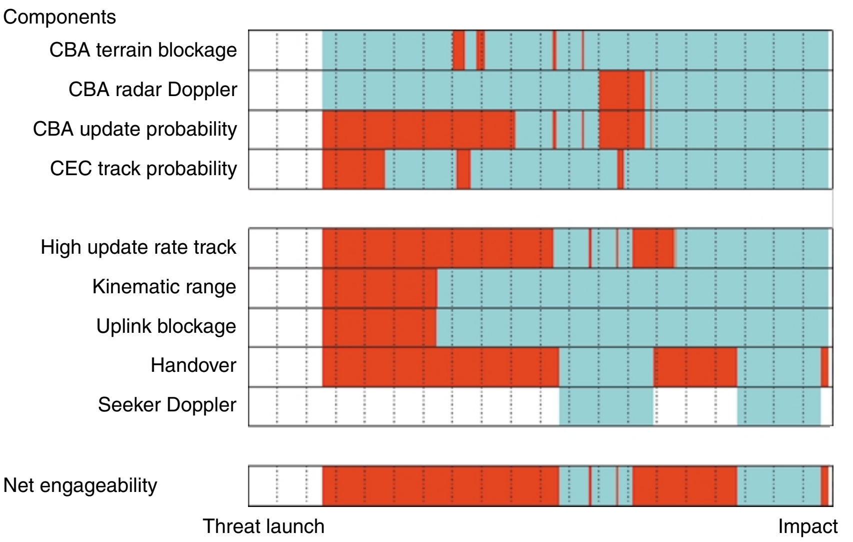

Figure 6. Representative data from a postflight analysis display. Once the process was modeled, the success and contribution of each component in the system (see, e.g., Fig. 5) could be displayed and compared.

ADSAM process. Prior to this effort and during its development, CEC modeling had relied on processing the actual recorded radar measurement data from sea-based, land-based, and airborne sensors. Using the same algorithms to determine CEC composite track probability as operational units, the new CEC model allowed the modeled data to be input from each Program Office–approved sensor model and provided useable composite track information to begin the modeling of the engagement process. Figure 7 indicates the functions in the CEC process, with those modeled for ADSAM shown in blue. Additional functions not yet modeled may be added in the future.

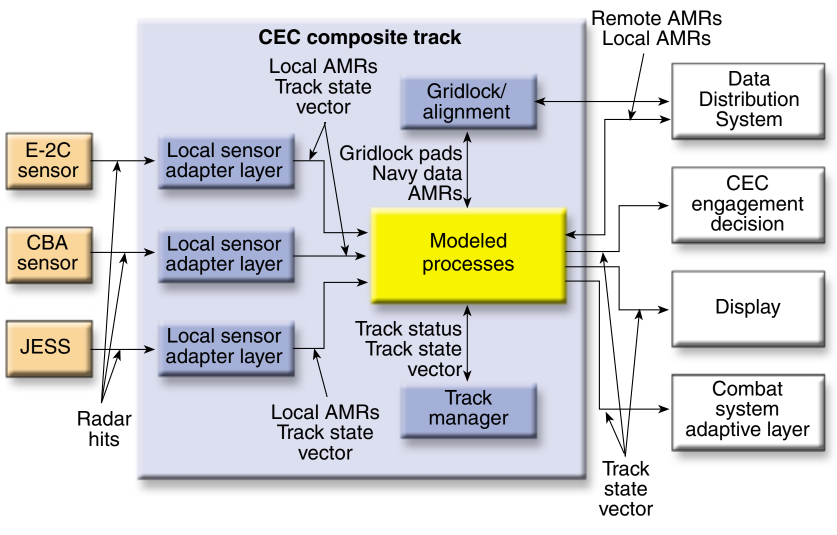

Figure 7. CEC Composite Track Filter Model. The critical factor in the ADSAM process is the requirement for composite track generation through the CEC System. In this study the modeled surveillance results from each sensor were provided in the standard Associated Measurement Report (AMR) format to the composite track filter. The process then applied the same algorithms as those used in the Fleet to generate the composite tracks. (Blue indicates that the effect was incorporated into the model.)

Normally the first WALEX audience in a yearlong study cycle comprised naval O-6/Captain-level Action Officers. An O-6/Captain/Colonel-level Joint Action Officer WALEX followed. O-6-level WALEXs focused on technical aspects of the analysis, component representations and validations, technical ramifications, and initial operational considerations. After the O-6 exercises, a series of naval and joint Flag/General Officer WALEXs was conducted, for which the focus shifted from technical issues to operational issues such as command responsibilities, interservice interoperability, and rules of engagement. A typical issue raised by at least one General Officer, however, was that even though it was possible for the Navy to now shoot that far inland, who was going to let them do so? This concern led to the identification of (1) critical issues in Joint Air Defense coordination policies and procedures and (2) concepts of Area and Regional Air Defense, among others. Eventually these issues were incorporated into other WALEXs, for example, by the Navy to develop Area Air Defense doctrine and by the Joint Theater Air and Missile Defense (TAMD) Office to develop a prototype Joint TAMD doctrine. Subsequent Flag briefings were provided to senior Navy and Joint audiences, up to and including the (then) Under Secretary of Defense for Acquisition and Technology, Paul Kaminski.

THE ADSAM/NAVY OCMD STUDY METHODOLOGY, 1998

Two advances in analysis methodology were added during the 1998 ADSAM Study cycle. First, it was expanded to consider three possible Aegis shooters, each with three different weapon options (i.e., concepts of interceptors). This required the development of a Distributed Weapons Coordination

(DWC) process, beginning with the formulation of an algorithm to estimate the probability of successful intercept for each type of weapon from each shooter at any given instant (Fig. 8). Typical results from the algorithm for just one enemy missile are shown in Fig. 9. This was followed by a recommendation of which ship should shoot, with which type of weapon. The algorithm also allowed the analyst to identify why the recommendation was made (Fig. 10).

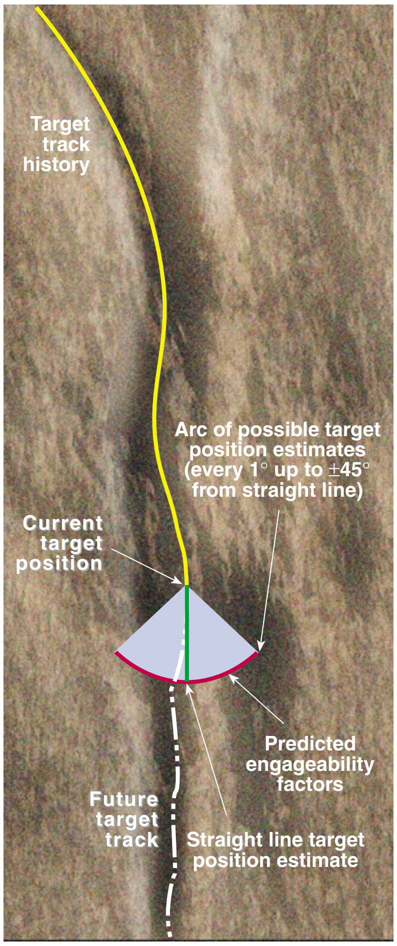

Figure 8. Predicted engageability process. Unlike postflight analysis (see Fig. 6), the need for engagement prediction required the study team to compute the probability of successful intercept for every point to which the target could move during the flight time of the interceptor. This was done every 0.25 s for approximately 90 potential intercept points. Factors considered here are, for example, handover uncertainty, seeker-received power density, seeker Doppler, spillover power density, and rear reference signal.

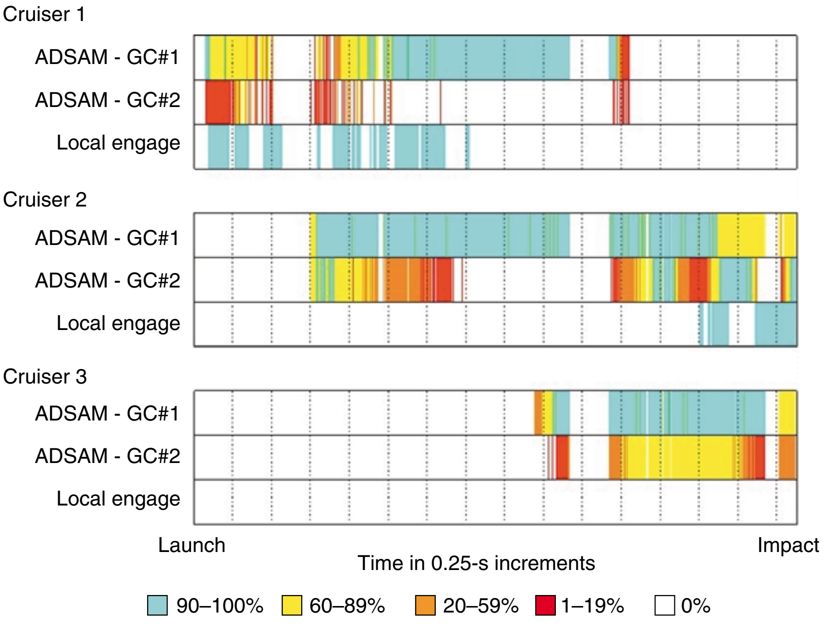

Figure 9. Engageability prediction: representative data for one trajectory. Once computed for each trajectory (and with each intercept option having different guidance choices, denoted by GC), and for each potential launch platform, the data were compared to identify where intercept success was greatest and where DWC was required.

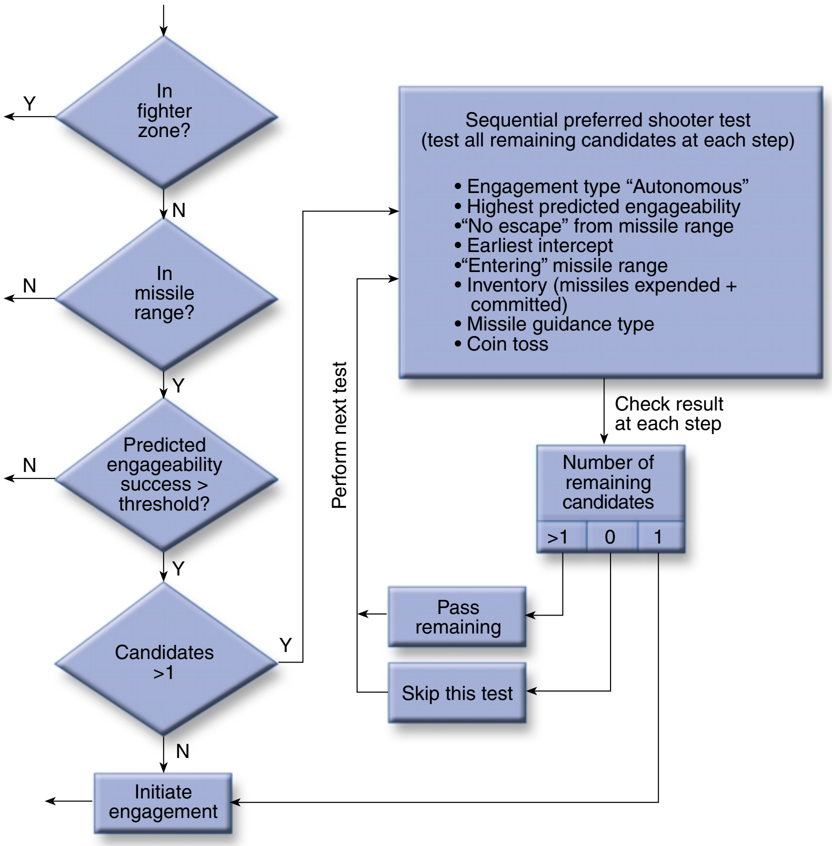

Figure 10. Preferred shooter recommendation/typical criteria prioritization. Once the engageability prediction process was completed, points indicating the simultaneous availability of more than one shooter or weapons option required a procedure to recommend which ship should shoot, with which weapon, and why. The prioritized set of criteria shown was developed and used for the 1998 ADSAM Study. This was not an attempt to specifically set the criteria for all situations, and further work is ongoing to better refine the process and its level of flexibility.

The DWC process was initiated if the engagement prediction algorithm indicated that, at specific 0.25-s intervals, multiple opportunities for successful intercept existed simultaneously. These ranged from one shooter having multiple weapon choices to all three shooters with three successful weapons options. Once this situation occurred, a prioritized list of decision criteria was used for the recommendation (Fig. 10). For the 1998 study cycle, a representative list of decision criteria was developed using such items as "highest probability of successful engagement," "first intercept," and "highest level of magazine remaining." It was recognized that future analyses and DWC development would have to be able to examine results using different or reprioritized criteria and that the on-scene commander would require this same flexibility.

Results provided numerous conditions where nonintuitive recommendations were made. When analysts examined the recommended shooters, one shooter was sometimes selected over another (at half the range of the first shooter) because it had less of a problem with seeker Doppler. In another case, a shooter was selected to fire behind itself because the intercept prediction indicated a higher probability of successful intercept. These kinds of decisions may not have been made by a commander operating unassisted in a quick-response situation.

Another advance in the 1998 ADSAM/OCMD Study was inclusion of the air-to-air component of TAMD. With participation by NAWC, China Lake, California, sensor pictures derived in the ADSAM modeling process could be provided to the center's high-fidelity models of aircraft, airborne fighter radar, and air-to-air interceptor to represent their engagement. Results were returned to APL for display and inclusion with surface-to-air results. The air-to-air component, although not integrated into the DWC process in 1998, is expected to be integrated in future phases of the ADSAM Study.

THE FUTURE OF THE ADSAM METHODOLOGY

The ADSAM methodology is modular and has been adapted in each annual cycle to address sponsor requests for systems analysis. For example, in 1997 under Joint Chiefs of Staff (JCS)/J8 sponsorship, systems such as Patriot and Aerostat/JLENS were examined. The results were used in a JCS/J8 OCMD Study. Future ADSAM analysis is expected to add AWACS and expanded air-to-air models, and to increase the participation of Patriot, JLENS, and other air defense systems. The ADSAM methodology can also be used in TAMD analyses through the addition of all-service or multiservice Ballistic Missile Defense systems.

Finally, while the methodology has been used to examine air defense problems, the basic concept can be applied to others like anti-submarine, anti-surface, strike, and electronic warfare to provide the true system-of-systems physics-based, high-fidelity, credible results needed in those fields.

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