



# Distributed Weapons Coordination Conceptual Framework

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**T**his article describes the systematic approach being taken at APL to formulate and comparatively assess distributed weapons coordination alternatives. The trade space being considered is described in terms of a simple taxonomy for defining and grouping coordination methods that have common characteristics. The ultimate goal in exploring distributed weapons coordination is to provide the automated decision support technology and related operational concepts that are necessary elements of true network-centric warfare. Efforts to date have focused primarily on establishing a modeling and simulation basis to allow for concept exploration and analysis. Initial battle effectiveness results obtained so far from Monte Carlo runs using the developed model are encouraging.

## INTRODUCTION

Theater Air and Missile Defense presents significant challenges to U.S. and coalition military forces throughout the world, driven primarily by the proliferation and evolving technical sophistication of ballistic and cruise missiles. References 1 and 2 provide assessments of current and projected theater missile capabilities that may be deployed by potential adversaries. Steady improvements in the range, accuracy, maneuverability, and stealthiness of tactical missile threats are expected, along with increased quantities in the arsenals of rogue nations. Improvements should also be anticipated in the maturity of potential adversary operational capabilities, including the infrastructure to support relatively advanced tactics in the use of these weapons (e.g., coordinated raids). The threat posed by tactical missiles is further compounded by the fact that these systems can be adapted to deliver weapons of mass destruction.

Theater Missile Defense (TMD) is recognized as an inherently joint mission. Joint doctrine defines TMD as

the integration of joint force capabilities to destroy theater missiles in flight or prior to launch or to otherwise disrupt the enemy's theater missile operations through an appropriate mix of mutually supportive passive missile defense, active missile defense, attack operations, and supporting command, control, communications, computers, and intelligence measures.<sup>3</sup>

Explicit in this definition is the requirement for integrated force action. Individual weapon and sensor systems, even if highly capable, are not the full solution to fielding an effective defense against theater missiles. An operational situation in a littoral theater is depicted in Fig. 1. Distributed weapons coordination (DWC) applied to an architecture that allows for the coordination of active air defense elements will

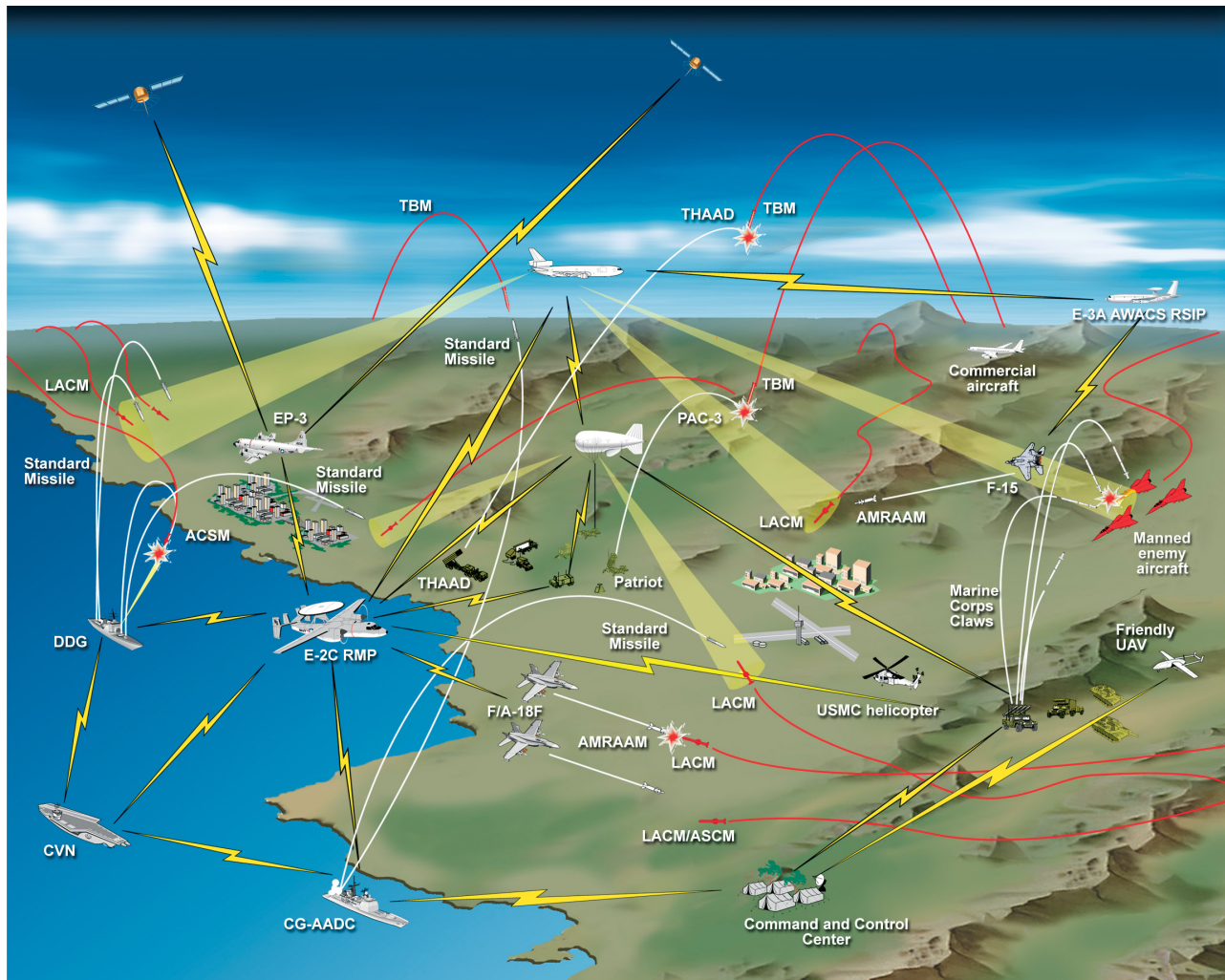


Figure 1. Joint integrated air defense environment.

meet the objective to provide automated coordination among surface and airborne sensors and weapon systems to execute engagements in a joint integrated air defense environment.

Since the kamikaze attacks in World War II, it has been evident that part of the fundamental solution to an overwhelming air attack is automated coordination among all the sensor and weapon assets available to a force. The current approach to DWC draws heavily on decades of APL scientific and engineering thought, investigations, and prototyping efforts that have addressed various aspects of the force coordination problem. The Laboratory is the Technical Direction Agent for the Force Anti-Air Warfare (AAW) Coordination Technology (FACT) and Cooperative Engagement Capability (CEC) programs. The origin of these programs can be traced back to the Battle Group AAW Coordination (BGAAWC) program that began in the late 1970s.<sup>4,5</sup>

APL also led systems engineering efforts for the Overland Cruise Missile Defense (OCMD) program. This work included the initial definition of DWC concepts

and emphasized the critical dependence of OCMD on coordinated and cooperative engagements.<sup>4</sup> From 1997 to 1999, the Laboratory developed an innovative distributed engagement decision method for assigning engagements to a force encountering raids of tactical ballistic missiles (TBMs). The method was specified for implementation in CEC before CEC was descoped from the Navy Area Theater Ballistic Missile Defense (TBMD) program.

Current tasks to develop DWC concepts will build on the solid foundation of innovation in air defense and battle force coordination that APL has led for many years. The DWC effort focuses on weapons coordination alternatives for the time and resource (sensor and weapon) constrained problem of active defense against tactical missiles.

This article outlines the primary objectives and desired operational characteristics of weapons coordination that are independent of specific methodology or implementation. Next, an overall trade space is defined for exploring a variety of alternatives within the

top-level functional areas of coordination. DWC concepts are defined within the context of this trade space. Finally, the use of modeling and simulation to support weapons coordination analysis is briefly discussed.

A list of key measures of effectiveness (MOEs) and measures of performance (MOPs) is included in this discussion along with a brief description of the use of three-dimensional visualization. An overview of current efforts to develop and demonstrate innovative DWC concepts is also provided. Several related articles in this issue of the *Digest* provide more detailed descriptions of selected aspects of the DWC project.

## BASIC CONCEPTS AND OBJECTIVES OF WEAPONS COORDINATION

Coordination among defensive elements is required to fight effectively as an integrated missile defense force. In the context of the DWC project, weapons coordination refers to processes for the management and selective application of available sensor, weapon, and command and control resources to detect, track, evaluate, and engage theater missile threats in flight. The term encompasses algorithms, functions, interfaces, and information exchange requirements that must have common implementations within combat systems across all of the services with the goal of achieving optimal force effectiveness.

Although force constituents and specific theater conditions may vary, the primary objectives of weapons coordination are to

- Minimize unengaged threats (free riders) while also minimizing unintentional redundant engagements
- Increase individual engagement effectiveness
- Enhance situational awareness while also decreasing confusion
- Maintain depth of fire

Coordination methods that are designed to minimize both unengaged threats and redundant engagements should increase the ability to handle large or dense raids while also extending sustainability. Individual unit effectiveness will be enhanced by coordination schemes that select engagements with a higher probability of success. The cumulative result should be an increase in overall force effectiveness. Individual unit decisions should be made with an understanding of the capabilities and intent of other units. The timely exchange of tactical information is essential to providing extended situational awareness. Robust correlation and deconfliction methods are required to minimize ambiguity in situational information. Finally, unit placement should, as much as possible, provide for multiple salvo opportunities by the force, each followed by kill assessment. Defense in depth is a necessary component of active defense as defined by joint doctrine.<sup>3</sup>

Coordination schemes provide the specific mechanism for managing and applying available depth of fire.

Myriad possible algorithms, techniques, and operational procedures may be devised to apply to the coordination problem. Choosing the most promising methods is a matter of considering both effectiveness (see above) and operational characteristics. Desirable operational features for any coordination scheme are responsiveness, consistency, graceful degradation, and weapon/sensor independent functionality.

To be responsive, coordination schemes must be in sync with unit-level fire control loop processes. Coordination decisions should also be adaptive and react to changes in the tactical situation (e.g., new or maneuvering threats). Achieving consistency implies that all units arrive at the same conclusions regarding who should shoot at what. There should be no ambiguity in threat designations, threat priority, or engagement assignments. Force coordination should gracefully degrade by automatically adapting to the temporary or permanent loss of individual unit contributions. Individual units should seamlessly revert to autonomous action when coordination within the force is not possible. Coordination processes should not depend on system-specific characteristics or on specific combinations of systems. If all units are plug-and-fight relative to coordination, asset placement options will be maximized and force commanders will have greater flexibility in designing a defense. Independent functionality should also reduce life-cycle costs by minimizing the extent of modifications when systems are added or updated.

These general objectives are intended to provide a common basis for assessing the potential operational benefits of different coordination schemes. Quantifying the performance of proposed coordination schemes involves the evaluation of specific MOEs and MOPs that are both system and situation dependent. The comparative assessment of schemes involves relating analytically derived MOEs and MOPs to the general objectives and operational features described previously. Ultimately, the potential benefits of recommended schemes must be weighed against projected cost, both in dollars and in the relative difficulty or complexity of implementation over the life cycle of affected systems. In general, the impact of coordination must be considered through all phases of the kill chain. Basic kill chain functions for a single combat system engaging a single threat are shown in Fig. 2.

The Area Air Defense Commander (AADC) has the primary responsibility of planning and executing air defense and, in conjunction with joint component commanders, for the disposition of TMD assets in a joint task force. The challenge is to provide defense in depth that is sustainable. During the collaborative planning process, the choices available for weapon and sensor coordination will influence the placement of forces,

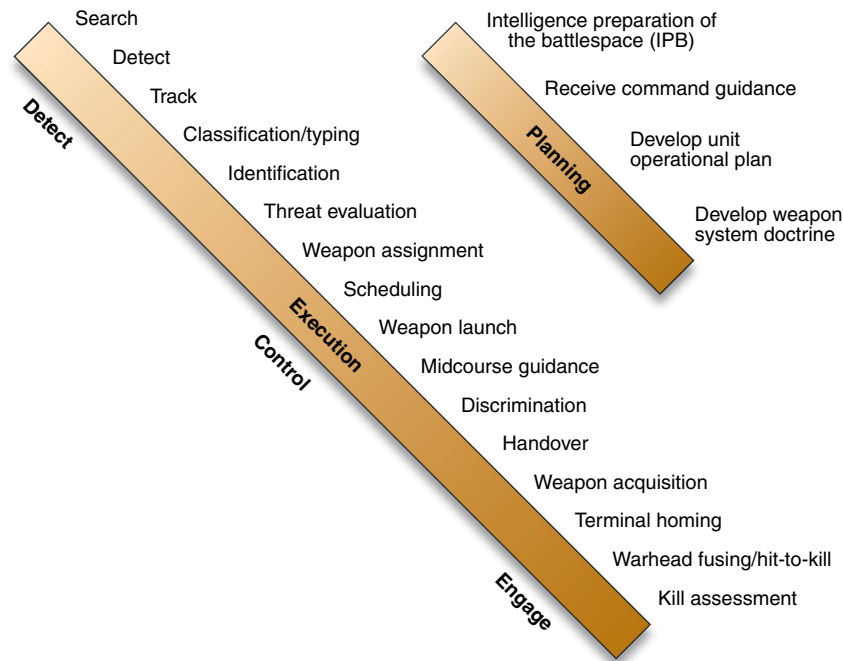


Figure 2. Kill chain functions.

development of weapon system doctrine, and establishment of required networks. The threat evaluation/weapon assignment (TEWA) functions form the core of the unit-level engagement decision process and, therefore, are also the central functions for coordination. Rules, procedures, and operational assignments established during the collaborative planning process are translated at the unit level into weapon system doctrine. Unit-level weapon system doctrine drives TEWA processes during execution. To fight effectively as a force, these rules, procedures, and assignments must be implemented consistently across all participating units.

The goal in exploring weapons coordination alternatives is to provide the automated decision support technology and related operational concepts that are necessary elements of true network-centric warfare. However, the problem space is quite large, even when pared down to consider only active defense against tactical missiles. Many possible approaches to coordinating the actions of multiple defensive units may be imagined. Schemes as simple as establishing fixed, nonoverlapping engagement zones have been employed in the past. However, given the evolution of both threat and defensive capabilities, coordination processes that are more reactive to changes in the tactical situation may significantly enhance force performance.

## DISTRIBUTED WEAPONS COORDINATION CONCEPT DEVELOPMENT

Beginning in FY2000, the Office of Naval Research (ONR) initiated a multi-year effort to develop and

analyze innovative concepts for DWC as part of the Missile Defense Future Naval Capabilities Science and Technology (MD FNC S&T) program. APL was tasked to lead the formulation of DWC concepts and their analysis through modeling and simulation. In conjunction with this effort, the Navy Theater-Wide Program Office provided tasking to analyze engagement coordination concepts for Navy upper-tier TBMD. The basic premise underlying this effort may be stated as follows: *Dynamic coordination and cooperation among dispersed defensive elements, supported by timely and accurate information exchange, will produce higher levels of force effectiveness and efficiency than could be realized by the independent action of those same elements operating within the limits of organic capability or within*

*the bounds of static, constrained coordination methods (e.g., fixed engagement zones).*

Different coordination methods may be broadly categorized as static or dynamic depending on whether they are preplanned and unvarying or are reactive to situational changes. Methods may also be used in either centralized or decentralized modes depending on whether key decision processes reside at a single command and control unit or at the individual weapon system level. Decision processes may depend on system-level metrics. These metrics may be estimated using system performance models embedded within the decision process or may rely on the exchange of metrics generated at the unit level. DWC concepts are defined here to be dynamic, decentralized, and reliant on the unit-level generation and exchange of performance metrics.

The consideration of a wide range of weapons coordination alternatives is required to objectively evaluate the relative benefits of DWC concepts. Therefore, a systematic approach is being taken to develop and comparatively assess weapons coordination concepts. This approach is based on separating the problem into three top-level functional areas: common threat evaluation (CTE), preferred shot recommendation (PSR) (or force-level weapon assignment), and sensor coordination. These correspond to the threat evaluation, weapon assignment, and sensor control functions that are essential elements of the single engagement kill chain (Fig. 2).

CTE, PSR, and sensor coordination extend engagement decision processes beyond single platform boundaries. They determine what should, what may, and what will be engaged, as well as what resources will be committed to engage from a force rather than a local

perspective. For each top-level functional area, specific algorithms, required information, and overall process flow will be examined during the course of the DWC project. The next three subsections describe general taxonomies for formulating alternatives for CTE, PSR, and sensor coordination. Collectively, they define the overall trade space being considered as part of the DWC effort (Fig. 3; Table 1).

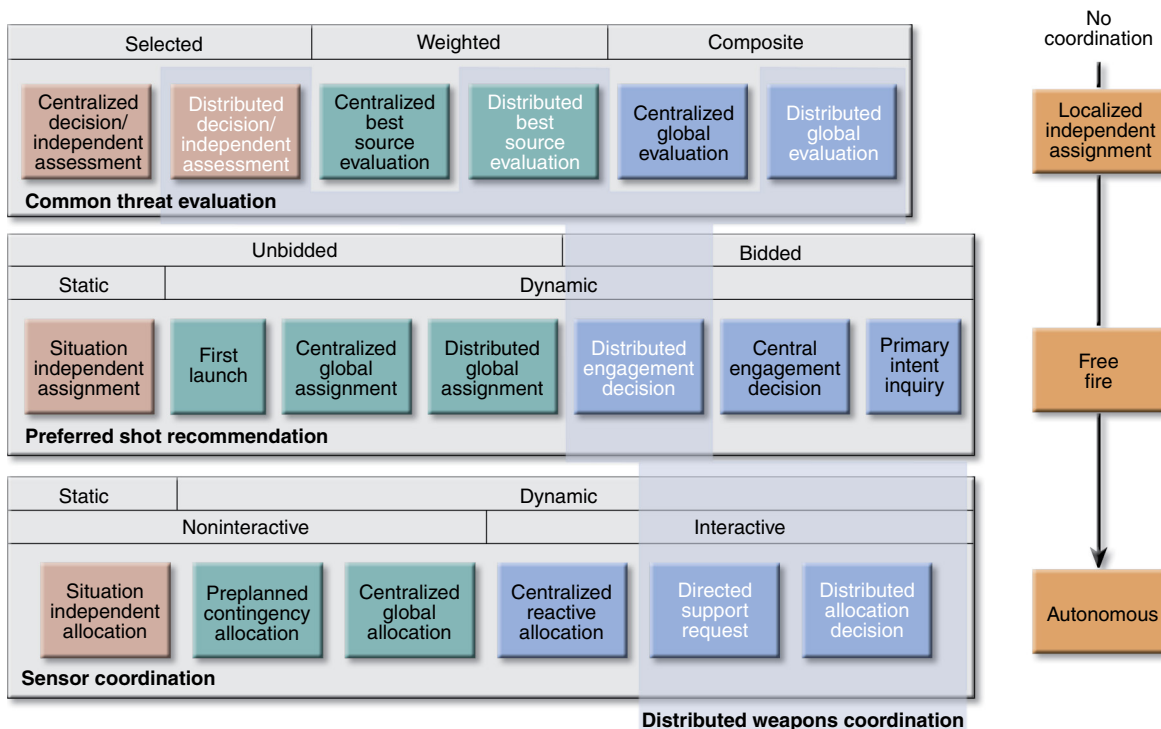
**Common Threat Evaluation**

The threat evaluation function determines what objects are candidates for engagement, determines whether engagement is allowed, and assigns relative priorities to those objects designated as threats. Threat evaluation directly depends on track characterization processes and track kinematics. Track characterization processes determine track category (e.g., space or air), type (e.g., SCUD-B, M-9, F-16), and identification (e.g., friendly, hostile). “Common” threat evaluation means that doctrine has a force-wide scope, processing considers multisource information, and procedures are implemented in an identical or functionally equivalent way among coordinating units. The objective of CTE is to provide consistent threat designations and priorities across the force.

Threat evaluation may be separated into the processes for threat assessment and threat prioritization. Threat evaluation comprises doctrinal procedures that are based on prevailing rules of engagement. Algorithms

and rules for assessing whether airborne objects are threats depend on track category. Assessment of TBM tracks is relatively straightforward because their flight paths are predictable and they are readily identifiable as hostile. In simple terms, if an object is following a ballistic trajectory that carries it above the atmosphere for some portion of its flight and it is likely to fall on something you care about, it is a threat. Threat evaluation for air-breathing vehicles, such as fixed-wing aircraft or cruise missiles, is more problematic. The flight paths of these types of vehicles are inherently unpredictable, which makes it very difficult to discern intent, especially at long range. Combat identification is a more complex process for air tracks than it is for TBM tracks. The confidence associated with maintaining unambiguous identification of air tracks is thus a complicating factor in making common engagement decisions across the force.

The basic threat assessment process for a TBM currently involves ballistically projecting the trajectory of the designated primary object in a TBM track cluster to estimate both launch and impact points. If the predicted impact point, taking into account track accuracy, is within a threshold distance from any defended assets, the track is declared to be a threat. Priority for engagement may take into account the priority of threatened defended assets or the probability that the TBM is carrying a weapon of mass destruction based on point of origin, typing, or other *a priori* knowledge. Limiting



**Figure 3.** Categories for weapons coordination methods. The DWC-specific categories are highlighted as a subset of this trade space.

**Table 1. Weapons coordination methods.**

Terms	Definitions
Common threat evaluation	
Selected	Threat assessment involves choosing from independent unit designations.
Weighted	Threat assessment is based on highest-confidence source information.
Composite	Threat assessment is based on fusion of multisource information.
Preferred shot recommendation	
Static	Preplanned and fixed; weapon/threat pairings are determined based on conditions that are insensitive to situational changes. Static schemes must be unbidded.
Dynamic	Rules for determining weapon/target pairings are reactive to situational changes. Pairings may change as a raid unfolds.
Unbidded	Shot selection process occurs without exchange of estimates of capability among participating units.
Bidded	Shot selection process depends on the exchange of estimates of capability that are calculated locally by each participating unit and then transmitted to remote units.
Sensor coordination	
Static	Predetermined and fixed; sensor utilization is determined based on conditions that are insensitive to situational changes.
Dynamic	Rules for determining sensor resource allocation are reactive to situational changes. Sensor tasking may change as the tactical situation develops.
Noninteractive	Sensor resource allocation occurs without exchange of estimates of need or capability among participating units.
Interactive	Sensor resource allocation depends on the exchange of estimates of need or capability that are calculated locally by each participating unit and then transmitted to remote units.

factors for the basic process include track accuracy and selection of the primary object from the track cluster associated with a launch event. CTE of TBMs is dependent on the use, across the force, of consistent (unambiguous) track data and common doctrine regarding defended areas and priorities.

Threat assessment procedures for air tracks will likely involve tests of combinations of factors, including track state (position, course, speed), track history, changes in flight profile (altitude, acceleration), vehicle type, and identification. Differentiating threats from friendly, neutral, or even hostile but nonthreatening air traffic is a significant challenge. Determining the probable targets of air-breathing threats may be very difficult because of the inherent unpredictability of their flight paths. Track history (track state data as a function of time) and associated attributes such as type and identification will provide key inputs to threat evaluation. However, sensor horizon limitations, terrain masking, and maneuverability can significantly degrade the detection capabilities of individual sensors, making it difficult to maintain continuous track. Combat identification is a difficult but critical process for air-breathing vehicles. Uncertainty or ambiguity in identification seriously complicates and may significantly delay obtaining actionable results from the threat evaluation process. Extending threat evaluation to a force-wide level further complicates an already difficult process.

The continuity, consistency, and confidence in force-wide track attribute data and the consistency of force-wide doctrine are expected to be driving factors affecting the performance of CTE methods when applied to air tracks.

Specific category-dependent threat assessment and prioritization algorithms will be developed and examined as an integral part of the DWC task. For DWC, the rules and criteria applied to qualify objects as threats must have a common implementation among coordinating units. Given a set of algorithms and rules, the CTE process may be implemented in a variety of ways. CTE methods may be generally grouped into the six categories shown in the first major section of Fig. 3.

The first two categories include methods in which threat designations are selected from independent unit level assessments.

*Centralized decision/independent assessment.* Individual units assess air and space tracks and provide threat recommendations to one master unit. The master unit selects from unit-level recommendations to designate and prioritize threats. The master unit disseminates a force-wide prioritized threat list to subordinate units.

*Distributed decision/independent assessment.* Units independently assess tracks and designate probable threats and associated priorities. All units exchange threat

recommendations. A common decision algorithm designates and prioritizes threats based on cumulative recommendations. Each unit maintains a force-wide prioritized threat list.

Weighted CTE methods base threat assessment on source information with the highest confidence. For example, Unit A has the highest track quality and reporting responsibility for a given TBM track. Therefore, all units use the track data and predicted impact point from Unit A for threat assessment. The weighted CTE categories include:

*Centralized best source evaluation.* One master unit assesses object attributes from selected sources to designate and prioritize threats. The master unit disseminates a force-wide prioritized threat list to subordinate units.

*Distributed best source evaluation.* All units exercise a common decision algorithm to designate and prioritize threats based on object attributes from own-unit or selected source(s). Each unit maintains a force-wide prioritized threat list.

Composite methods base threat assessment on the fusion of multisource information. The composite CTE categories include:

*Centralized global evaluation.* One master unit assesses tracks to designate and prioritize threats. Assessment is based on fused object attributes from multiple sources. The master unit disseminates a force-wide prioritized threat list to subordinate units.

*Distributed global evaluation.* All units exercise a common decision algorithm to designate and prioritize threats based on fused object attributes from multiple sources. Participating units exchange attribute data. Each unit maintains a force-wide prioritized threat list.

In our analysis, methods in any of the CTE categories may also be compared to performance based on the autonomous action of individual units. Therefore, one additional category representing no coordination is included for completeness.

*Localized independent evaluation.* Threat evaluation is not coordinated. Each unit assesses and prioritizes threats considering only its own assigned defended assets or areas. Independently developed doctrine and priorities may be applied. Exchange of information with other units is not required.

### Preferred Shot Recommendation

The PSR function determines who should shoot at what. This process specifically couples threats to unit-weapon-shot opportunity combinations. For example, the preferred shot against track number 4201 is from

DDG 51 using a Standard Missile 2 (SM-2) Block III based on earliest predicted intercept time. At the unit level, weapon assignment is a straightforward process of pairing the right weapon type to a given threat. This relatively simple decision process becomes more complicated when extended to the selection of target-unit-weapon-shot opportunity combinations across a force for multiple, concurrent threats.

The basic problem is to allocate to available units the engagement responsibility for all known threats given unit-level resource constraints (e.g., each weapon system has a finite number of interceptors and a maximum number of supportable simultaneous engagements). Unfortunately, other constraints may also complicate the problem and limit the possible solution space. Geometry or timing may preclude all threats from being engageable by all defending units. Certain engagements may seriously conflict with other unrelated operations or result in undesirable collateral damage.

The complexity introduced by practical constraints generally makes the shot selection problem intractable for pure textbook methods taken from the fields of operations research or artificial intelligence. However, these disciplines may offer useful methods for formulating the force weapon selection problem in ways that allow modified solution techniques to be applied.

The number of methods that can be imagined for PSR is virtually limitless. Therefore, an attempt has been made to define the scope of possible schemes in terms of a few general categories. This approach is similar to one outlined during the Joint Composite Tracking Network study for comparing different engagement coordination schemes (R. Rothrock, presentation to JCTN Study Systems Employment Subpanel, 13 June 1997). Within a given category, many possible schemes may be devised, but at some level all of them will exhibit common operational characteristics. Hybrid schemes may also be devised where coordination is accomplished by methods from more than one of the basic categories, depending on the specific units involved. If the operational characteristics of methods in one category can be demonstrated to have better performance than the other categories, the search for specific PSR algorithms can be concentrated in that category. Conversely, methods that fall into categories that consistently demonstrate poor performance may confidently be eliminated from consideration.

The seven basic categories shown in the middle section of Fig. 3 are classified according to whether they are reactive to changes in the tactical situation (dynamic vs. static), involve centralized or decentralized decision making, and depend on the exchange of estimates of capability (bidden vs. unbidden). Specific schemes in some of these categories may depend on the determination of launch and intercept times or may involve adjusting salvo size (method of fire) as part of the PSR process.

In some schemes, the eligibility of units for reengagement after a miss may be constrained by rules governing the reaction to kill assessment from other units.

Static PSR schemes are preplanned and fixed. Weapon-threat pairings are determined based on conditions that are insensitive to situational changes. Static schemes must be unbidded.

*Situation independent assignment.* Preplanned, fixed conditions are applied for determining threat-weapon pairings; e.g., exclusive engagement zones (geographic and/or altitude layered).

Dynamic PSR schemes involve rules for recommending target-unit-weapon-shot opportunity combinations that are reactive to situational changes. Preferred shots may change as a raid unfolds. Unbidded shot selection processes occur without the exchange of estimates of capability among participating units. Dynamic unbidded categories include:

*First launch.* The unit that launches first against a given threat broadcasts engagement status to other units. The other units defer scheduled engagements against the same track (if it is not already too late). Examples of this method include CEC Navy AAW and Navy Area TBMD Aegis-Aegis (BL6P3).

*Central global assignment.* One master unit internally models the capabilities and schedules of all units. The master unit determines which unit(s) should engage and disseminates engagement orders. A prime example in this category is the AADC prototype probability of intercept ( $P_i$ ) leveling scheme. Engageability and availability windows are computed for each threat and firing unit, and then this scheme attempts to achieve the same cumulative  $P_i$  level against all threats concurrently by scheduling shots for all capable units. In an operational situation, the AADC would issue specific force engagement orders based on the recommendations of the  $P_i$  leveling scheme.

*Distributed global assignment.* All units internally model the capabilities and schedules of all other units. Each unit exercises a common decision algorithm to determine which unit(s) should engage (e.g., Aegis-Aegis enhanced Link-16 concept).

Bidded PSR schemes involve shot selection algorithms that depend on the exchange of estimates of capability calculated locally by each participating unit and then transmitted to remote units. The dynamic bidded categories are:

*Distributed engagement decision.* All units exchange engagement MOPs. Each unit exercises a common decision algorithm that evaluates bids to determine which unit(s) should continue engagements and which should defer (e.g., CEC design for Navy Area TBMD [not implemented]).

*Central engagement decision.* One master unit receives engagement MOPs from all units. The master unit evaluates bids to determine which unit(s) should engage and disseminates engagement recommendations (e.g., Patriot intra-battalion [Information and Coordination Control Center, Engagement Control Station]).

*Primary intent inquiry.* The secondary system questions the primary and then adjusts method of fire (firing policy) based on the response of the primary system regarding intent to engage. Specific schemes that have been proposed in this category are based on exchange between only two units at a time (e.g., Patriot post-deployment build [PDB]-5+/Theater High Altitude Area Defense [THAAD] C1; Aegis [BL6P3]/THAAD C1).

In our analysis, methods in any of the PSR categories may also be compared to performance based on the autonomous action of individual units. Therefore, one additional category representing no coordination is included for completeness.

*Free fire.* Shot selection is not coordinated. Each unit independently selects and schedules engagements without regard for the actions of other units. Exchange of information with other units is not required.

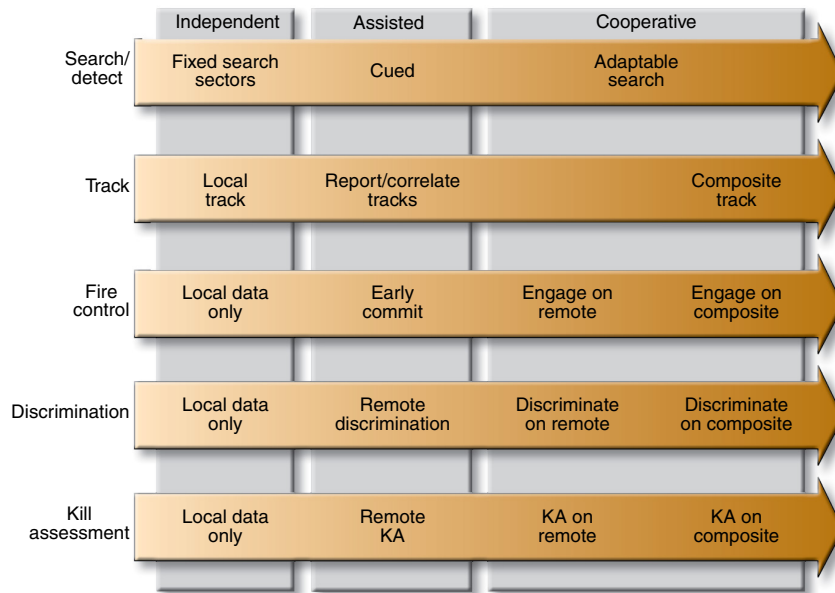
A comparative analysis of selected PSR alternatives for Navy Area TBMD engagements was performed in FY2001. Four specific alternatives were examined: (1) free fire, (2) a simple sectorized variant in which defending ships have unique defended asset assignments, (3) first launch (shoot-and-shout), and (4) a distributed engagement decision variant in which preferred shots are selected based on an ordered set of estimated performance and status criteria. In addition, a relatively simple force-wide threat evaluation process for TBMs was modeled. Moskowitz et al., this issue, provide more detailed descriptions of the scenario and options exercised for this analysis along with a discussion of the Monte Carlo results.

## Sensor Coordination

The sensor coordination function allocates sensor resources across the force to maintain a common, clear, and accurate tactical air picture to support engagement coordination. Sensor coordination is also required to support cooperative engagements.

A variety of sensor functions must be performed to produce and maintain a tactical air picture and to support engagements (Fig. 4). The engagement capacity and battlespace of individual weapon systems may be seriously constrained by organic sensor limitations. Individual limitations may be mitigated by various levels of assisted or cooperative action among sensors on the





**Figure 4.** Sensor functions: independent, i.e., function is performed with local system capability only; assisted, i.e., information available from external sources is used to support local system functions, but external sources are not directly tasked; and cooperative, i.e., external sources directly contribute and may be directly tasked to support local system function.

same or different platforms. The options depicted in Fig. 4 for each of the major sensor functions represent a spectrum of capabilities rather than discrete modes. For example, a given combat system may generate local tracks from organic sensor data obtained by searching established search sectors while concurrently accepting remote tracks over a data link from external systems. Remote tracks that do not correlate with a local track might then be used to generate a cued acquisition volume for an organic sensor.

Coordination of sensors for surveillance and tracking functions should allow for the more efficient use of available resources by balancing individual sensor loading with accuracy needs. Sensor coordination would also be important for supporting cooperative threat assessment and cooperative identification processes. Cooperative engagement concepts (see the boxed insert) may extend the effective range of weapon systems beyond the limits of organic sensor capabilities. The benefits of composite identification and engage-on-remote (EOR) for battle group AAW have been demonstrated by the Navy's CEC. Through real-time sensor netting, CEC enables an Aegis ship to engage inbound air threats using fire control quality sensor data from another Aegis ship.

The feasibility of another advanced cooperative engagement concept, air directed surface-to-air-missile (ADSAM), has been demonstrated in the Mountain Top live-fire tests conducted at the Pacific Missile Range Facility in Kauai, Hawaii. At the force level, coordination is needed to efficiently allocate sensor resources to support cooperative engagement opportunities.

Cooperative discrimination may enhance the ability of an individual system to target the lethal object in a TBM cluster. Cooperative kill assessment may enhance the ability of a single system to effectively determine engagement outcome. If either of these concepts proves to be feasible, sensor coordination will be needed to select and allocate remote sensors to support these functions (e.g., sensors with favorable geometry or capability for unique feature extraction).

The six basic categories for sensor coordination, shown in the lower section of Fig. 3, are classified according to whether they are reactive to changes in the tactical situation (dynamic vs. static) and whether they require exchange of information among participating units (interactive vs. noninteractive).

Static noninteractive sensor coordination schemes may be used for any of the main sensor functions and fall into the following category:

*Situation independent allocation.* Preplanned, fixed modes of operation for search and track functions. Preplanned, fixed, and possibly unique assignment of off-board sensors to support weapon systems for discrimination, fire control, and/or kill assessment functions. Examples in this category include fixed search sectors for surveillance and fixed track production areas.

Dynamic schemes involve rules for determining sensor resource allocation that are reactive to situational changes. Dynamic noninteractive categories are:

*Preplanned contingency allocation.* Limited, predefined alternative modes of operation for search and track functions. Activation of contingency options may be triggered automatically or by command direction. Limited, predefined alternatives for assignment of sensors to weapon systems for discrimination, fire control, and/or kill assessment support functions. Activation of contingency options is triggered by command direction.

*Centralized global allocation.* One master unit monitors the force tactical picture and assigns search, track, and engagement support modes to all sensors based on internal models of sensor characteristics.

Interactive schemes depend on the exchange of estimates of need or capability that are calculated locally by each participating unit to drive algorithms for recommending sensor resource allocation. Dynamic interactive sensor coordination categories include:

## DEFINITION OF TERMS

### Cooperation

The application of resources acting in a mutually supportive way to accomplish a single task.

### Cooperative engagement

An engagement that requires the mutually supportive actions of independently controlled assets for successful execution (e.g., air directed surface-to-air missile [ADSAM] or air directed air-to-air missile [ADAAM]).

### Coordination

The selective application of multiple resources to act in response to multiple, concurrent tasks.

### Engagement coordination

The preferential selection, scheduling, and execution of engagements when multiple defending units are capable of engaging concurrent threats. Selection among existing engagement options is based on the application of universally established rules and criteria to the current, commonly understood tactical situation.

### Engage-on-remote (EOR)

The use of fire control quality sensor (or track) data from one or more nonorganic sources to support engagement functions. Specific advanced EOR engagement concepts include:

*ADSAM*: airborne sensors provide over-the-horizon tracking and fire control quality data to a surface weapon system to support engagement with a surface-to-air missile. The launch platform retains control and provides midcourse guidance to the surface-to-air missile.

*ADAAM*: airborne sensors provide tracking and fire control quality data to an airborne weapon system to support engagement with an air-to-air missile.

*Forward pass*: after initiating an engagement using remote data, the launching platform transfers the guidance and control of a missile in flight to another system.

### Engage-on-composite

The use of fused, multisource sensor (or track) data to support engagement functions. Data may come from organic and/or nonorganic sources. Data from individual contributing sources may or may not be of fire control quality; all that is required for engage-on-composite is that the fused result is fire control quality.

### TMD operational elements<sup>3</sup>

*Passive defense*: measures taken to posture the force to reduce vulnerability and minimize the effects of TM attack.

*Active defense*: operations undertaken to protect against a TM attack by destroying TM airborne launch platforms and/or destroying TMs in flight.

*Attack operations*: operations undertaken to destroy, disrupt, or neutralize TM launch platforms and their supporting structures and systems.

*Command, control, communications, computers, and intelligence (C4I)*: systems used to coordinate and integrate the joint force capabilities to conduct and link passive defense, active defense, and attack operations.

*Centralized reactive allocation*. One master unit monitors the force tactical picture and assigns search, track, and engagement support modes to all sensors based on MOPs and status information received from the individual sensor platforms.

*Directed support request*. Individual units request support from selected offboard sensors for specified search, track, or engagement functions; sensor systems accept or reject support requests based on availability and capability (e.g., CEC EOR for Navy battle group AAW).

*Distributed allocation decision*. All units receive MOPs and status information from all other units. Each unit exercises a common decision algorithm to determine allocation of sensor resources to support search, track, and engagement functions across the force.

In our analysis, methods in any of the sensor coordination categories may also be compared to performance based on the autonomous action of individual

units. Therefore, one additional category representing no coordination is included for completeness.

*Autonomous*. Sensors are not coordinated. Each unit independently allocates own-sensor resources, considering only local needs relative to own-sensor capabilities.

## DWC Categories

Collectively, the categories defined in each of the three top-level functional areas provide a framework for a broad range of weapons coordination concepts. In each area, only certain categories have the primary DWC characteristics of being dynamic, decentralized, and reliant on unit-level metrics. As shown in Fig. 3, the subset of categories encompassing DWC concepts includes the following: for CTE, distributed decision/independent assessment, distributed best source evaluation, and distributed global evaluation; for PSR, distributed engagement

decision; and for sensor coordination, directed support request and distributed allocation decision.

## ANALYSIS OF COORDINATION CONCEPTS

Modeling and simulation provides the only practical mechanism for comparative analysis of the wide range of possible weapons coordination methods outlined in this article. The essential analytical challenge is to quantify the potential benefits of any proposed coordination schemes under realistic tactical conditions. However, “realistic” does not necessarily mean modeled at the highest possible fidelity. Rather, it means that the factors or combinations of factors that affect performance are represented at levels that demonstrate performance sensitivities.

At the outset of the current effort, the APL DWC project team and the sponsors mutually agreed that existing modeling and simulation tools were inadequate for the proposed tasks. Therefore, initial efforts concentrated on the development of the APL Coordinated Engagement Simulation (ACES). The first phase of ACES includes features to specifically support the level of DWC concept formulation required to meet initial program objectives for Navy TBMD, but the overall design was created with the flexibility to encompass the scope of additional capabilities that will ultimately be required to analyze the full spectrum of Theater Air and Missile Defense missions. The primary impetus in the development of ACES was the need to accurately represent unit-level engagement decision, control, and execution processes in a complex environment (i.e., multisensor, multiweapon, multitarget, multimission). The capabilities and features of ACES are more fully described by Burke and Henly, this issue.

Fundamentally, any decision process is only as good as the information that drives it. Important aspects of the analysis process for comparing different decision schemes are to understand performance across a spectrum of perfect to imperfect knowledge and to examine performance across a broad range of operational conditions. Appropriately representing factors that individually or cumulatively result in degradations in the perceived situation is critical because that perception drives decisions.

Weapons coordination processes are inherently sensitive to the quality of the tactical air picture. Tracks and tracked object attributes are the basis for engagement decisions. For active defense, most of the factors that directly influence engagement decisions manifest themselves in various aspects of the tactical air picture. Ambiguity in the air picture can have a significant, negative impact on the performance of coordination schemes. In general, the potential ripple effects of processes that occur throughout the detect-to-engage kill

chain must not be ignored when comparing the performance of different weapons coordination methods.

The ACES environment has been designed to reflect these sensitivities. The detection, networking, and track correlation and reporting features of ACES are described in greater detail by McDonald et al. and Bates et al., this issue. The selection of appropriate scenarios is critical to ensuring that a necessary and sufficient range of operational conditions is tested. Engler et al., elsewhere in this issue, address the scenario selection process that has been applied for DWC studies.

## Measures of Effectiveness and Measures of Performance

The MOEs and MOPs that have been identified to support analysis of DWC concepts are the metrics that will be used to assess the relative benefits of alternative schemes. As this project progresses, the applicable list of metrics will be updated when required. Distributions and summary statistics (e.g., minimum, average, maximum, and standard deviation) of MOEs and MOPs will be extracted from Monte Carlo runs. Items will be reported by threat, unit, and force level and also as functions of time, as appropriate.

Top-level force MOEs include quantitative measures related to the capability of the force to negate a raid of air or missile threats. These MOEs are identified in Table 2. Other conventional MOEs, such as the number of kills and the probability of raid annihilation, may be simply and directly derived from the principal MOEs listed in the table.

Force MOPs include quantitative measures related to the use of force resources to defend against air and missile threats. These measures may be related to overall force performance or may be system or process specific. The list of MOPs that are potentially relevant to DWC analyses is extensive, and a detailed discussion is beyond the scope of this article. A few examples are given in Table 2.

## Air Picture Metrics

Each unit has a different perspective of the air picture over time based on own-sensor detection and tracking processes and exchange of track data with other units via available data link or sensor networks. Top-level metrics for characterizing the air picture are given in Table 3. These metrics are consistent with the single integrated air picture (SIAP) attributes that have been defined by the SIAP Systems Engineering Task Force.<sup>6</sup>

## Visualization

The interpretation and presentation of weapons coordination analysis results are supported by the use of three-dimensional visualization. The System Analysis, Visualization, and Advanced Graphics Engineering (SAVAGE) Laboratory at APL provides the capability

**Table 2. Measures of effectiveness and measures of performance relevant to DWC analysis.**

Measure	Description
MOEs	
Leakers	Number of lethal objects that successfully reach defended assets
Free riders	Number of lethal objects not launched against (subset of leakers)
Unengageable	Number of lethal objects not launched against that were unengageable by any defensive assets (subset of free riders)
Defended assets hit	Number or percentage of defended assets hit by at least one lethal object
MOPs	
Overengagements (unintentional)	Number of salvos launched in excess of prescribed force firing doctrine
Engagement loading	Number of engagements (i.e., number of salvos) per unit
Inventory expended	Number of interceptors used over the course of a given scenario
Radar resource utilization	Percentage of radar resources used as a function of time and radar task

**Table 3. Air picture metrics.**

Metric	Description
Completeness	Percentage of ground truth objects that are in track by at least one unit as a function of time
Ambiguity	Number or percentage of multiple track designations and track merges relative to number of ground truth objects in track
Continuity	Percentage of time a ground truth object is in track and track attribute data are maintained without interruption (i.e., no drops, swaps, or merges)
Timeliness	Track data age (time since last update); distribution as a function of time

to render various aspects of DWC input scenarios and results into such three-dimensional graphic representations. The benefit of visualizations in the project is two-fold: (1) they allow the engineers who are creating the models to conduct a quick check of their work to ensure that everything behaves properly at a composite level, and (2) visualizations provide a coherent and efficient means of presenting results to sponsors and others in a form that generally allows quick comprehension of complex situations or interactions.

The visualization of DWC analysis results involves integrating the inputs and outputs of ACES with a representation of the engagement environment. This integration often highlights discrepancies between data formats of various entities. For example, the threats may be modeled in Earth-centered inertial coordinates, while the interceptors may be modeled in Earth-centered, Earth-fixed coordinates. Visualization of these two components on a representation of the engagement environment would easily highlight such a discrepancy and in such a manner that many other potential difficulties may be found that are of interest to the analysts.

The complexities of the engagement scenarios and the many variables resident in ACES provide for a large amount of information that is not easily conveyed in a conventional slide presentation. However, intelligent

application of visualization tools allows for the large amount of information to be presented in a concise and comprehensive manner. The audience sees the engagement scenario unfold as time progresses, with relevant metrics overlaid onto the visual graphics to provide insight into the situation. Single-frame excerpts from visualizations of a scenario played out with two different PSR schemes are shown in Fig. 5.

The visualizations can be paused, sped up, or slowed down, and may be viewed from virtually any angle. Thus, a presentation that would last several hours with many static slides may often be compressed into a single visualization that can be run in minutes.

## CONCLUSIONS

The future TMD family-of-systems architecture will include joint sensor, weapon, and C4I systems that will all play significant roles in the coordination of actions across the force. Defining those roles in terms of desired capabilities is a significant undertaking. The effort described in this article is focused on the development and analysis of algorithms, functional elements, interfaces, and information exchange requirements that must have a common implementation within systems from all of the services to enable dynamic, force-wide weapons coordination. It addresses technical challenges

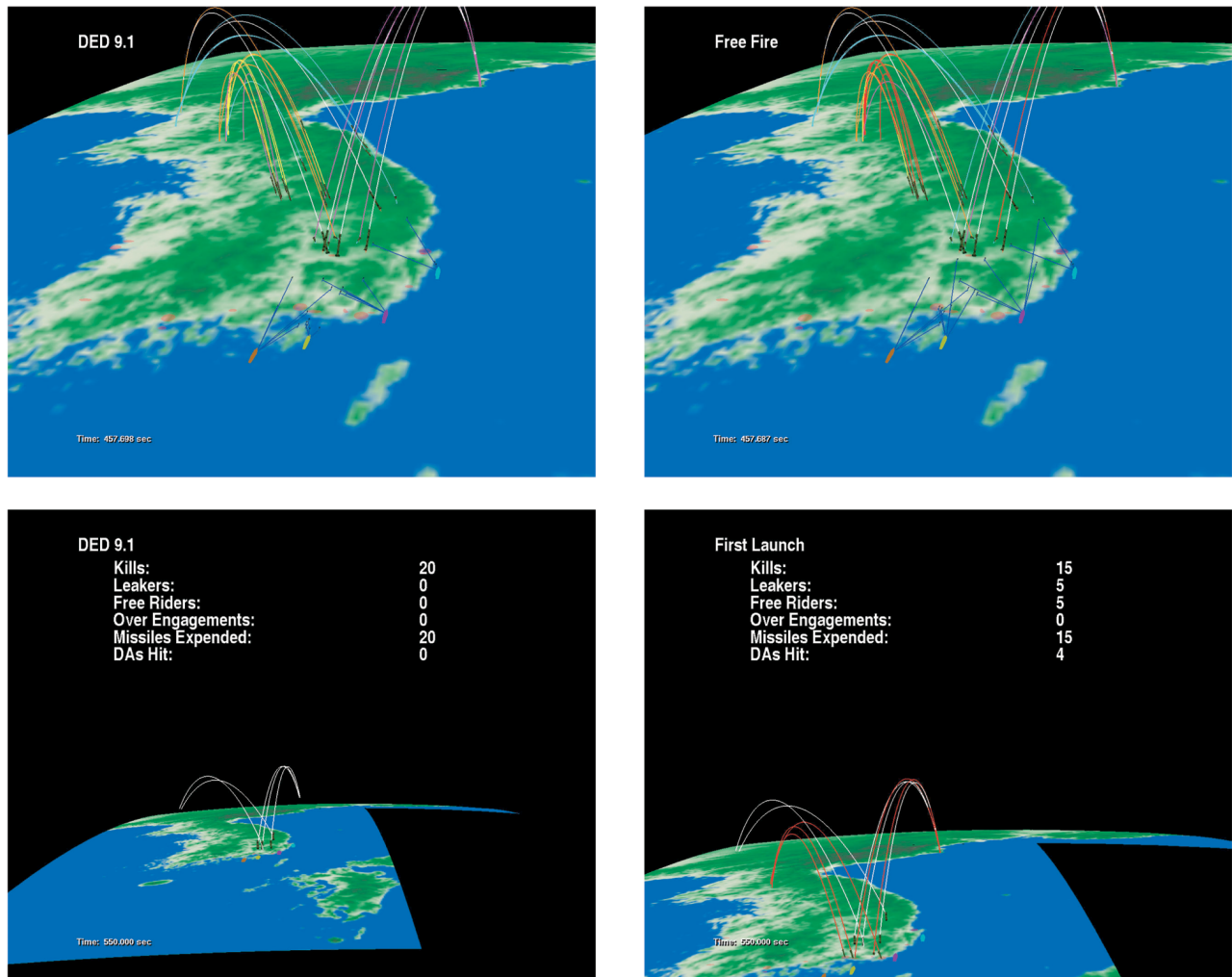


Figure 5. Single-frame visualization excerpts.

in defining an end-to-end process for DWC that includes the primary functional areas of CTE, PSR, and sensor coordination.

The DWC concept extends the traditional detect-to-engage sequence beyond the limits of individual platform capabilities to offer greater flexibility and robustness in the application of force firepower while ensuring the integrity of the fire control loop to put ordnance on target.

Initial DWC efforts for the ONR MD FNC S&T program have focused on a few selected algorithm alternatives in the context of Navy TBMD. However, the overall vision for DWC accounts for the fact that coordination is ultimately a multimission, multiservice problem. Current program plans reflect the goal of developing workable DWC concepts within the full context of Theater Air and Missile Defense. Over the next few years, DWC concept exploration will expand to include additional alternatives and the scope of analysis will be

extended to include joint assets and other air and missile defense mission areas.

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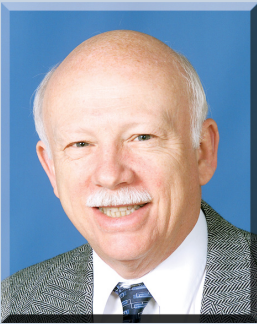
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