The Role of Serious Games in Ballistic Missile Defense

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Serious games have played an important role in the development of ballistic missile defense technology since the mid-1960s. At that time, Lincoln Laboratory initiated a series of games in which researchers assumed the roles of ballistic missile defense (BMD) system operators charged with mitigating a missile attack. Postgame analyses of gameplay led to increased understanding of the technology required to effectively identify and engage missile threats. Throughout the 1970s and 1990s, the BMD community concentrated on developing needed technology, and game playing fell into disuse. With the technology advancements of the 2000s, gameplay re-emerged as an effective way of determining how to exploit the new capabilities against an increasingly sophisticated adversary, and the Laboratory designed games that took advantage of new decision support tools.

The missile defense mission area at Lincoln Laboratory has exploited serious game playing since the early 1960s. The games took many forms and were used by Laboratory researchers to investigate ballistic missile defense (BMD) problems and develop and test solutions. New Laboratory staff, industry personnel, government employees, and warfighters who were invited to participate in the games also got hands-on experience with BMD concepts. Games played an important role during two time periods, separated by about 35 years, and consequently resulted in a wide range of game design and implementation that covered a broad spectrum of objectives. In the intervening period of BMD game-playing inactivity, significant advances in both BMD technology and the computer sciences enabled modern games to achieve a level of sophistication never imagined in the 1960s. Over that same period, the Ballistic Missile Defense System (BMDS) evolved from a simple configuration of radars and interceptors to become a "system of systems."

The Early Years

In the mid-1960s, the U.S. Department of Defense was in the initial stages of developing its first BMD system. Research and field measurement activities were characterizing the physics and observables that would eventually be used by the BMD sensors to identify threatening targets. Large-scale computing systems and the real-time software needed to control a complex BMD system were still in the development stage. The BMD community faced a major question: How does one extract the appropriate information embedded in the sensor data and utilize it in a logical framework capable of successfully engaging an incoming ballistic missile [1]?

During this time, Lincoln Laboratory was the major developer in BMD technology, while Bell Telephone Laboratories was responsible for designing, building, and deploying the actual BMD system. In 1963, Lincoln Laboratory initiated an effort that became known as the Engagement Exercises. The effort brought together Lincoln Laboratory scientists and engineers who were experts in the physics of missile and radar systems, and engineers from the Defense Research Corporation of Santa Barbara, California, who were specialists in the emerging field of missile and defense system computer simulation. These exercises took place prior to the advent of personal computers, and programming was tedious and limited to modest-sized mainframes. The games were played manually by competing teams, housed in separate rooms, relying on pencil and paper and having little or no computer automation available to them. Each game included a defense team, an offense team, and an umpire team. Offense-defense interaction was facilitated by the umpire team, whose members moved between the two competing teams to communicate individual team actions and determine the outcomes of decisions made by each team. (See William Delaney's Looking Back article on page 108 for a personal view of these exercises.)

Each game was preceded by several months of game preparation. The umpire team defined technology and resource constraints. With these constraints in mind, the offense generated weapon inventories and attack strategies, and the defense generated extensive sensor and system architectures, defining their associated measurement capabilities and engagement logic. Strategies were documented on paper with logic diagrams and precalculated decision thresholds.

Once the conflict (game) began, it took several days for the teams to complete the game. After the conflict ended, an extensive period of analysis determined what worked and what needed to be improved. This process generated insight into many facets of the defense system and highlighted technology areas that needed further development. The game was played once or twice a year and grew in sophistication with each cycle. The effort continued for approximately four years.

The Middle Period

For roughly the next 30 years, adversarial games did not play a significant role in the BMD mission area. The major activities within Lincoln Laboratory's program shifted to concentrate on the development of algorithms and the real-time field demonstration of techniques for the critical BMD functions of tracking, discrimination, and decision support. The demonstrations utilized two sophisticated computer systems—one system integrated with the radars at the Kwajalein Missile Range (KMR) in the Marshall Islands and the other located at Lincoln Laboratory. This work went through several iterations, starting with the Lexington Imaging System (LIS) and Kwajalein Imaging System (KIS) effort in the early 1980s and evolved into the Lexington Discrimination System (LDS) and Kwajalein Discrimination System (KDS) by the late 1980s. The LIS and KIS were focused on using state-of-the-art processing hardware to demonstrate the viability of real-time radar image formation. After the capability to produce images in real time was demonstrated, the systems continued to evolve to become the LDS and KDS, which were used to demonstrate a full complement of the critical BMD functions.

Over several years, Lincoln Laboratory conducted demonstrations using the KIS and then the KDS against a variety of realistic ballistic targets at Kwajalein. Prior to implementing the techniques at the KMR sensors, the Lexington system was used to conduct extensive studies, exploiting radar data recorded during live missions at Kwajalein and simulation inputs to make sure the techniques were ready for the live-time field demonstrations. The demonstrations and facilities were important for two reasons. First, they enabled the staff to create a toolbox of real-time software for implementing advanced signal processing and critical BMD algorithms. Second, the demonstrations required the development of the highest-fidelity target models that had been generated up to that time.

As part of the preparation for the field demonstrations, an extensive set of high-fidelity target simulations was developed, along with graphical user interfaces (GUIs), to serve as diagnostic tools for the experimental packages deployed to the field. With the advent of high-throughput computation and advances in high-speed signal processing, these demonstrations were the first in which advanced BMD concepts could

Lincoln Laboratory Simulation Tools

Ballistic Missile Defense Toolbox

These frequently used functions for BMD simulations include modules modeling the physics for ballistic trajectories, torque-free body dynamics, and maneuvering dynamics, as well as utilities for coordinate transforms, mathematical functions, signal processing, and tracking. The toolbox functions were optimized for speed and internally validated.

Lincoln Laboratory LL6D

This 6-degree-of-freedom missile simulation utilizes many of the BMD toolbox functions to create the trajectory files for an entire BMD threat complex. The LL6D emulates unitary boost, staging, object deployments, and individual object dynamics.

Augmented Point-Scattering Model (APSM)

The APSM uses a Lincoln Laboratory radar cross-section signatures-modeling format and a suite of signature interpretation software. Generating intensive scenes on the fly required new techniques because the industry standard signature format, Xpatch, required too much memory and did not, at the time, preserve the phenomenology of interest from pulse to pulse. APSM is based on a point-scattering model [2].

Optical Signatures Code (OSC)

The OSC is a national standard code that generates detailed infrared signatures and that models the output of space-based sensors and interceptor seekers.

Lincoln Laboratory Simulator (LLSIM)

The LLSIM is a simulation framework for generating BMD scenes for all phases of flight and all phenomenology types. LL6D, APSM, and OSC provide the trajectories, RF response for single objects, and infrared response for single objects. LLSIM uses these as inputs to create simulated radar and infrared sensor and data processing output, including multiple-object radar pulses and infrared sensor responses. In addition, discrimination algorithms and decision aids were implemented as part of the data processing. The LLSIM uses an xml file to define the threat and blue force (missile defense) laydown, including the sensors, interceptors, and command and control, and publishes the sensor output to a database for use in visualization software.

Lincoln Laboratory Visualization Interface and Scalable API (LLVISTA)

This visualization software package allows flexible configuration of graphical user interfaces. The tool was developed to decouple the user interface from the BMD scene-generation tools, accomplished via a publish/subscribe implementation. It is able to plot scrolling range-time-intensity, range-Doppler images, and feature/feature plots.

be executed in an autonomous fashion. The GUIs and high-fidelity target and environment models were essential to the success of these field demonstrations. Although the demonstrations were a significant step toward bringing advanced BMD capability to the field, they were limited to single-sensor architectures and remained scripted. A detailed account of these field measurement activities may be found in Chapter 9, Ballistic Missile Defense, of the Lincoln Laboratory history book [2]. The concepts of adaptive sensor architectures, multisensor system design, and centralized/hierarchical system control and decision making were yet to be formalized.

Advances made during this period provided a strong framework for the series of games that would come to fruition in the early 2000s. The core components of this framework are the Lincoln Laboratory 6-degrees-of-freedom (LL6D) trajectory generator, the Augmented Point Scattering Model (APSM), the BMD Toolbox, and the Lincoln Laboratory Visualization Interface and Scalable API (LLVISTA). These enablers were primarily focused on radar sensors.

The Modern BMD Games

In the 1960s, the BMD system employed two radars—a search and acquisition radar and a fire-control radar. These radars did not have much flexibility and handled targets by using a predetermined script with a limited degree of dynamic decision support. Consequently, game playing concentrated on understanding and developing the logic and decision strategy for the battle management functionality.

By the early 2000s, the BMD system concept had evolved, employing multiple radars operating at different frequencies and observing different phases of a threat trajectory. In addition, optical sensors were included as part of the sensing suite. A broad array of algorithms for the critical BMD functions was developed over the intervening years and was extremely sophisticated. Computational power and speeds had reached levels that would allow sensors to operate in a more dynamic and adaptive way. During this time, researchers investigated how to best exploit these new capabilities.

In 2001, adversarial game playing once again became active within the Lincoln Laboratory BMD community under Project Hercules, a national effort sponsored by the Missile Defense Agency (MDA) to advance the state of the art for the critical functions of the BMDS. Figure 1 depicts a notional representation of a generic BMDS. In a simplified view of the modern-day concept, the BMDS consists of a number of individual sensors that gather data about an incoming threat and attempt to identify the lethal target(s). The target state estimates and decision information are passed to a central battle manager where they are integrated with data from all available sensors to provide more complete situational awareness, upgraded fire-control track information, and improved target identification. This information is used to reallocate sensor resources and generate interceptor fire-control solutions for the identified threat targets.

The initial purpose of the modern BMD games was to support the development of sensor algorithms and system architectures that would result in enhanced capabilities for the BMDS. The idea was to understand how the human mind exploited sensor observations to identify the threatening targets while rejecting the accompanying nonlethal targets, and to capture that process so it could be incorporated into decision architectures. The modus operandi was for Lincoln Laboratory subject-matter experts (SMEs), selected from a variety of technical areas, to collaboratively solve specifically designed challenging threat scenarios. The SMEs included the following:

- Data analysts experienced in sensor observables exploitation who could determine relevant and important target characteristics
- Signal processing experts who understood how to extract critical information from sensor observations
- System engineers who understood the resource implications of engagement constraints

To provide motivation, the SMEs were organized into teams that would compete against one another, and trophies were awarded to the winners.

Game Formulation

The new generation of games became known as the red/blue (R/B) exercises. The primary objective of these games was to identify improvements in the sensor

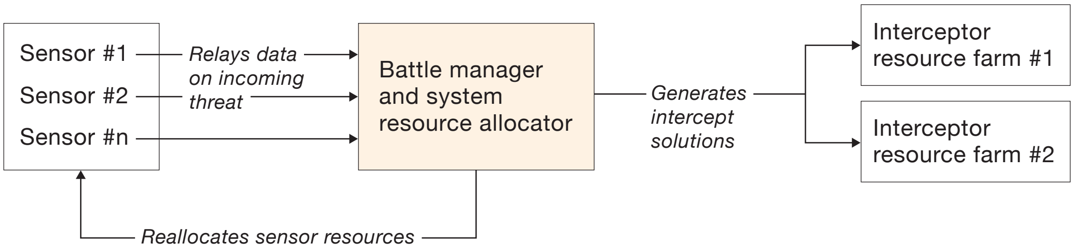


FIGURE 1. In this notional representation of a ballistic missile defense system, individual sensors gather data on an incoming threat and attempt to identify the lethal target(s). The sensor response for each target is passed to the battle manager, which combines data from each sensor to generate more complete situational awareness. This information is used to reallocate sensor resources, generate intercept solutions, and assign interceptors to specific targets.

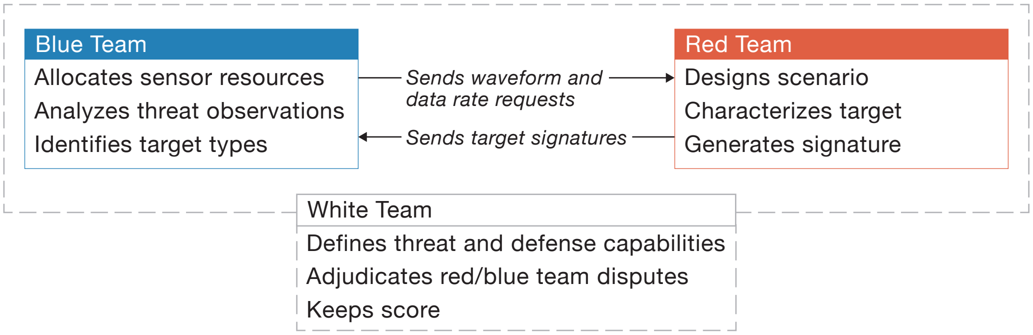


FIGURE 2. The team structure of a ballistic missile defense game includes red (offense), white (umpire), and blue (defense) teams.

decision architecture. Figure 2 provides an overview of the organization of the initial games and shows the responsibilities of the teams and the primary interactions between the teams. Several blue teams competed against each other to mitigate a common threat generated by the red team. The white team, similar to the old umpire team, postulated a BMD problem, and the red team had several months to define the threat and generate the sensor observables. The red team was composed of Lincoln Laboratory staff who worked with the MDA's threat engineering team, the intelligence community, and the Laboratory's Engineering Division. The red team reviewed the known offensive capabilities of peer and rogue nations, and worked diligently to ensure that any threat components incorporated into the game reflected the engineering capabilities of an actual adversary.

The generation of very high-fidelity simulation sensor observables was the most important and tedious part of the game. This task was critical because the games were intended to challenge the SMEs' ability to discriminate the targets on the basis of sensor observations. For the development process to have credibility, the information contained in the sensor signatures had to be as realistic as possible. The years of modeling experience obtained during the 1980s and 1990s in support of the Lexington Discrimination System development were critical to making the BMD games realistic and able to contribute to the development of BMD technology.

Prior to the game, the white team defined a scoring structure so that prizes could be awarded to the winning team. The game was played over two days and included a preparation phase and a postgame analysis phase. During the preparation phase, each blue team learned the capabilities of its sensor and the nature of the threat and defense problem. On the first morning, they were guided through a simple version of the game that contained no countermeasures. The blue team spent the afternoon developing its strategy for sensor measurement and data exploitation, and documenting the strategy with flow charts and decision graphs.

On game day, the red team was allowed to utilize countermeasures. Each blue team occupied a separate room in which a white team observer recorded the team's play. Once the engagement was underway, the blue team was permitted to make procedural modifications, and the white team documented the changes accordingly. During the postgame phase, the white team identified the strengths and weaknesses of the blue team's methodology in order to develop a better understanding of how to improve the sensor decision architecture. In addition, participants made valuable recommendations for algorithm upgrades and graphical user interface (GUI) improvements.

The Evolution of the BMD Game

The timeline continuing along the bottoms of the following pages provides a history of game development and highlights key features in the game's evolution. Several significant transitions in the level of game sophistication are described in the following text.

2001

DATE: 10/31

DESIGNATION: Red/Blue (R/B) 1

SENSOR SUITE: Midcourse (MC) radar

PURPOSE: Established best use of radar data to identify targets and seek discrimination ideas and features for red threat of interest

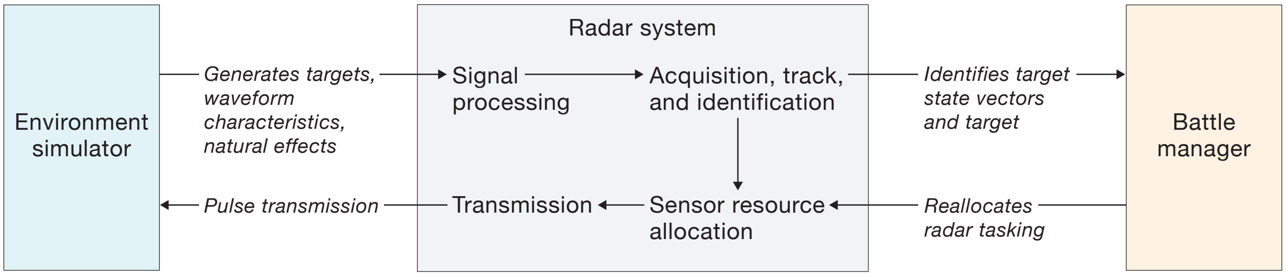


FIGURE 3. This notional representation of a ballistic missile defense sensor depicts the interplay between the environment simulator, the radar system, and the battle manager. The battle manager provides tasking to the radar, which allocates the resources (schedules the pulse-repetition frequency and desired waveform for each object) and then transmits the pulses. The simulator returns the multi-object threat complex response for each transmitted pulse to the signal processor, which compresses the pulse and adds the proper system noise. If objects are above the noise threshold, the detections are associated with existing object tracks. Long-term tracks receive target identification. This information is sent to the battle manager and may be used for the next resource period.

Early Radar Games (Red/Blue [R/B] 1, 2, 3, and 7)

The objective for the initial set of modern games was to understand the strategies that each team employed, with the intent of integrating the successful sections of the logic and processes into a decision architecture for a computer-controlled radar. The focus was to specify the data needed and decision logic required to correctly classify an observed target.

Figure 3 depicts a notional sensor configuration. The game software processed signal information from the target scenario and placed objects into track—an estimated trajectory based on the object's associated detections in range, azimuth, and elevation relative to the radar's boresight. The blue team managed the radar resources to collect the data necessary to support their decision architecture. The R/B 7 provided the software structure to integrate several of the advanced algorithms into a comprehensive software package. This package enabled the blue team to schedule algorithms so that the outputs could be used by the architecture. Equally important, R/B 7 allowed the white team to examine a variety of ways to exploit new concepts and evolve a best-practice approach.

Interceptor Games (R/B 4 and 6)

In late 2002, the game (R/B 4) still emphasized a single sensor but addressed a different sensing phenomenology by considering a multiband infrared (IR) sensor aboard a missile defense interceptor that targeted a multi-object threat complex. However, the interceptor was a moving platform with a limited field of view and the ability to divert to a given object in the threat complex. As the interceptor approached the complex, objects dropped out of the interceptor's field of view and escaped the interceptor's reach. To ensure adequate viewing time, the blue team managed the sensor field of view, the interceptor's approach vector to the complex, and containment for objects of interest. The R/B 4 was the first of two games focused solely on the IR seeker. In late 2004, R/B 6 included a visible-band optical sensor that allowed the blue teams to explore the utility of this additional capability.

2002

DATE: 02/14
DESIGNATION: R/B 2
SENSOR SUITE: MC radar
PURPOSE: Established best use of radar data to identify targets with long viewing time

DATE: 07/17
DESIGNATION: R/B 3
SENSOR SUITE: Forward-based (FB) radar
PURPOSE: Established best use of radar resources for a forward-deployed radar with limited viewing time

DATE: 10/27
DESIGNATION: R/B 4
SENSOR SUITE: MC infrared (IR)
PURPOSE: Used IR data for an intercontinental ballistic missile–class interceptor

System-Level Games (R/B 5, 8, 9, and 10)

The first multiple-sensor game was R/B 5, which was conducted in spring 2003. This game featured two radars, each with different sensor attributes (e.g., sensitivity, frequency) and located to allow the radars to observe the threat with different viewing geometries. The a priori sensor positioning provided the defense with a much richer set of observables and allowed for more sophistication in the decision support design than previous games. In this scenario, the blue teams did not contend with inter-sensor bias, i.e., slight imperfections in sensor pointing that could interfere with sensor-to-sensor object correlation.

The real-world challenges of sensor bias and correlating (mapping) objects from one sensor to another were introduced in 2005 with R/B 8. The blue teams faced a complex scenario for discrimination and a new challenge of imperfect sensor-to-sensor handover from forward-based radar to midcourse radar and from the midcourse radar to the interceptor. Along with choosing waveforms to help discriminate between objects, the blue teams adjusted the tracking resources (between none, low-resource, and high-resource track waveforms) on each object in the threat complex to help resolve correlation ambiguities.

In early 2007, the next major evolution of the game (R/B 10) included a multi-threat raid scenario. The red team devised five threats of varying complexity. The game was played in scaled real time, and additional decision aids were provided, including a prototype decision architecture and a more elaborate fire-control display than was used in previous games. The software provided estimates for object lethality and decision confidence while the fire-control display included interceptor availability and a dynamic interceptor-scheduling GUI. The white team observed how the blue team utilized the architecture output, concentrating on the human-machine interaction and the use of decision confidence measures.

In parallel to the large two-day version of the R/B games, the developers produced smaller-scale, one-hour games (mini-R/B or MRB) to play at various missile defense conferences, workshops, and courses. These venues included the Ballistic Missile Defense Joint Advisory Committee Meeting, later called the Air and Missile Defense Technology Workshop (AMDT), the Lincoln Laboratory BMD Technology course, the Missile Defense Sensors, Environments, and Architectures Conference (MD-SEA), and the National Fire Control Symposium. The first three of these mini-games, MRB 1–3, were scaled-down versions of full games.

MRB 4 introduced a new era in R/B small-scale games. It included an emulation of MDA's newest proposed system architecture. The portable game was used to educate participants about the BMD system's operation and to study human interaction with the proposed architecture.

In May 2009, MRB 5 was introduced and included an update that allowed blue teams to assign specific roles and functions to individual team members to more realistically reflect missile defense system operation. The Lexington Decision Support Center provided separate control rooms for the functional subteams of each blue team to perform their roles during gameplay. The software was updated to pipe the same threat information to each room, which displayed an emulated sensor or system function output. For each blue team, two to three members served as the operators for a forward-based radar, two to three members served as the operators for a midcourse sensor, and two to three served as the command, control, battle management, and communications (C2BMC)/ground-based midcourse defense fire-control operators. In addition, each sensor

2003

DATE: 05/08
DESIGNATION: R/B 5
SENSOR SUITE: FB and MC radars
PURPOSE: Performed system-level discrimination for multiple radars with perfect target handover between radars

2004

DATE: 03/17
DESIGNATION: R/B 6
SENSOR SUITE: MC IR and visible radars
PURPOSE: Investigated utility of visible data for discrimination

DATE: 10/22
DESIGNATION: R/B 7
SENSOR SUITE: MC radar
PURPOSE: Integrated advanced algorithms into R/B framework and observed analyst utilization of algorithms and approaches to schedule waveforms for input into algorithms

team communicated with the fire-control operators via text and graphical communications and used voice links between the rooms for discussion.

By May 2010, this distributed approach to the operations was enhanced to include two airborne infrared (ABIR) unmanned aerial vehicles that fed data into the C2BMC node. This game focused on sensor resource management, in particular using the two ABIR vehicles for tracking in a raid environment. The goal was to provide sufficient track quality to engage the maximal number of threats in a raid. For AMDT 2011, the ABIR element was augmented with a discrimination capability.

The BMD Games Infrastructure

The initial version of the modern BMD games was quite modest, residing on a small network of laptop machines. It exploited many of the target signature simulation and discrimination tools that had been developed in support of Lincoln Laboratory's long-standing BMD discrimination technology program. Many of these software packages were first used in the Lexington Discrimination System and evolved in quality with each field experiment.

As the games evolved, they incorporated more sophisticated threats, sensor processing algorithms, and decision support tools, and eventually required a larger network of computing hardware to accommodate gameplay needs. In a parallel effort, Lincoln Laboratory was developing a BMD Decision Support Laboratory that exploited the capabilities of the Laboratory's high-performance computing facility [2]. This facility, known as the Lexington Decision Support Center (LDSC), was the culmination of a multidecade evolution of Lincoln Laboratory simulation tools that were developed in support of discrimination technology. The LDSC consisted of several separate, but highly integrated, laboratories. One laboratory was dedicated to the development of very high-fidelity sensor and environment simulations. A second laboratory was dedicated to multisensor information fusion and battle management, while a third housed the development and testing of decision support tools for BMD.

In May 2009, a distributed defense system game was developed for the Lincoln Laboratory Joint Advisory Committee meeting and was installed in the new LDSC facility. The advantage of this instantiation was that it allowed a team to be broken into subteams and placed in separate rooms with specific displays for the team's sensor control, data fusion and battle management, and weapon-control functions. The displays were linked by voice communication in a manner similar to the way a distributed weapon system would be implemented. This arrangement allowed for the development of additional interactive displays that addressed how the separate subteams could communicate efficiently.

2005

DATE: 05/17

DESIGNATION: MRB 1

SENSOR SUITE: MC radar

PURPOSE: Scaled down the version (both in time and complexity) of R/B 7; first game at Ballistic Missile Defense Joint Advisory Committee (BMD JAC). Used during BMD technology courses hosted at Lincoln Laboratory

DATE: 12/7

DESIGNATION: R/B 8

SENSOR SUITE: FB and MC radars and exoatmospheric kill vehicle (EKV)

PURPOSE: Introduced complexity into the game with blue teams performing radio-frequency (RF)-to-RF handover and RF-to-IR handover. Added low pulse-repetition frequency (PRF) and high PRF track waveforms to allow for more handover control. Added user interface for correlation and sensor bias removal

System Resource Allocation Games (AMDT 2012)

By 2012, the game had changed radically. Its focus had shifted from the details of sensor data exploitation to the investigation of high-level system issues, such as preplanned disposition of assets and the real-time allocation of defense resources during battle. The resource allocation game introduced a number of new features and was the first game that combined air and missile defense. It was also the first game in which a red team played interactively against a blue team and in which random events were used to model the fog of war, i.e., uncertainty in situational awareness experienced by participants in military operations. Since sensor data exploitation was no longer an objective to be explored in these games, no attempt was made to model the signatures of the various targets or to model various decision algorithms.

Game Play

The actual game-playing experience has changed significantly during the game's history. Early versions employed projected displays and allowed the clock to be stopped for team discussions. By 2007, R/B 10 featured a reduced tempo clock and an uninterrupted timeline. At the game's most mature stage, individual interactive desktop displays portrayed information unique for each operator position.

Figure 4 shows a blue team on game day. The game control operator sits at the console at the left. The right screen displays selection options for the radar resources. On the left and center screens are wideband radar displays that depict radar returns from several targets. The blue team analyzes this information to determine the team's future moves.

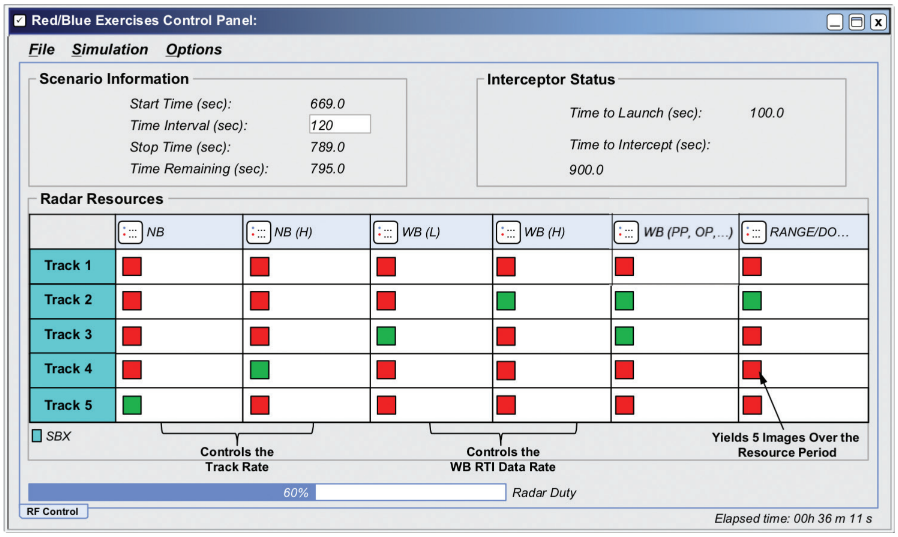
FIGURE 4. The blue team analyzes target observations, assesses engagement status, and prepares radar resource requests for the next time interval.

2006

DATE: 05/03
DESIGNATION: R/B 9
SENSOR SUITE: FB and MC radars
PURPOSE: Added impact-point prediction

DATE: 05/22
DESIGNATION: MRB 2
SENSOR SUITE: FB and MC radars
PURPOSE: Scaled down the version of R/B 8; presented at BMD JAC 2006

DATE: 10/25
DESIGNATION: MRB 3
SENSOR SUITE: FB and SM-3 radars
PURPOSE: Introduced a regional scenario with compressed sensor and playing timelines. Played at Missile Defense Sensors, Environments, and Architectures Conference, at the MDA for the program office, at the BMD JAC, and in Huntsville, Alabama. More than 100 participants



Scenario Information

Start Time (sec): 669.0
Time Interval (sec): 120
Stop Time (sec): 789.0
Time Remaining (sec): 795.0

Interceptor Status

Time to Launch (sec): 100.0
Time to Intercept (sec): 900.0

Radar Resources

	NB	NB (H)	WB (L)	WB (H)	WB (PP, OP,...)	RANGE/DO...
Track 1	🟥	🟥	🟥	🟥	🟥	🟥
Track 2	🟥	🟥	🟥	🟩	🟩	🟩
Track 3	🟥	🟥	🟩	🟥	🟩	🟥
Track 4	🟥	🟩	🟥	🟥	🟥	🟥
Track 5	🟩	🟥	🟥	🟥	🟥	🟥

SBX

Controls the Track Rate

Controls the WB RTI Data Rate

Yields 5 Images Over the Resource Period

60% Radar Duty

Elapsed time: 00h 36 m 11 s

FIGURE 5. The radar control panel displays current status and waveform option buttons, including narrowband (NB) low-resolution waveform, wideband (WB) waveform, low pulse-repetition frequency (PRF) transmission (L), and high PRF transmission (H). Each option results in different levels of information quality. Green indicates that the sensor is going to employ that waveform on the given track, and red indicates that the sensor is not using the waveform on the given track.

Figure 5 depicts the GUI used to manage the resources of a generic long-range, wideband radar. Each choice results in a different fraction of radar resource devoted to the selected function. Typically, higher radar resource allocation provides improved levels of information quality. The trade-off between resource allocation and information quality is established by the choice of sensor technology assumed during the game design phase. The blue team then schedules when to collect the data on the objects in track and decides how to optimize information gain under current resource constraints. The green and red toggle boxes indicate how the blue team opted to schedule and collect data on the targets in track. The left-hand column identifies the track file, and the row shows the resources the team assigned to that particular target. In this case, Track 2 represents a target that is in track, and the team opted to gather the highest-quality wideband discrimination data that the radar is capable of collecting. At the bottom of the control panel, the Radar Duty bar indicates the fraction of total radar resource being consumed by all tasks currently executing, and shows the radar to be operating at slightly more than half its full capacity.

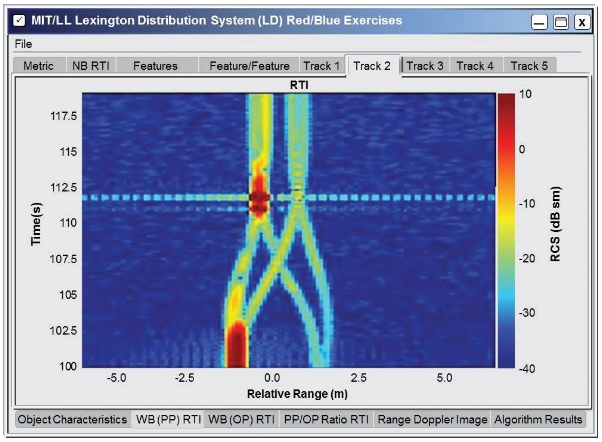


FIGURE 6. This display shows a wideband radar range-time-intensity plot for Track 2.

Figure 6 displays a range-time-intensity (RTI) plot for a target being tracked by the radar. At the top of the

2007

DATE: 04/18

DESIGNATION: R/B 10

SENSOR SUITE: FB and MC radars, fire control

PURPOSE: Premiered scaled-down real-time games and more elaborate fire control with inventory and multiple weapon sites. Unveiled first raid scenario, featuring automation of decision logic and correlation to investigate interaction of humans with decision aids

2008

DATE: 05/15

DESIGNATION: MRB 4

SENSOR SUITE: FB and MC radars, fire control

PURPOSE: Scaled down the R/B 10 version to teach newly adopted missile defense object-targeting concepts

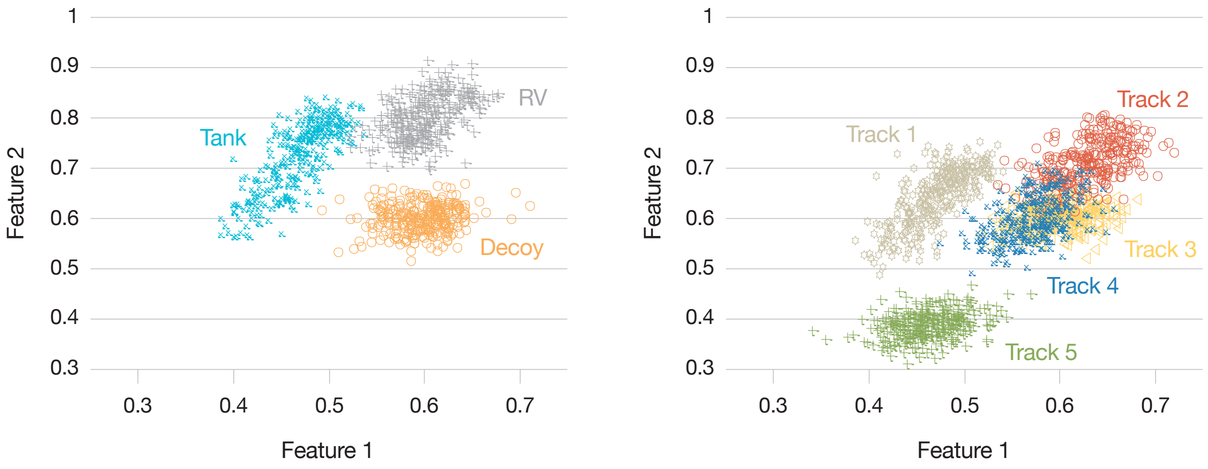


FIGURE 7. A feature/feature plot shows a comparison of extracted features for each object in a scene. In this example, the left panel displays labeled a priori training information, and the right panel displays game-day information from objects in track with unknown types (marker colors are used to indicate that the features are from the same tracked object; colors are randomly assigned).

screen, the team can select from several tabs to examine particular plots of the data collected by the sensor. The first four tabs provide information for the entire sensor collection. The Metric tab provides altitude versus time; the narrowband low-resolution waveform, NB RTI, tab has the radar cross-section (RCS) response for the collection of objects in the scene in range over time; and the Feature/Feature tab provides a comparison of the extracted features (such as depicted in Figure 7) for each object in the scene. These plots are updated in real time with data from the radar's scheduled waveforms.

The remaining tabs exhibit object-specific output. In the example given, there are five tracks, and the tab for Track 2 is selected. There are six additional tabs along the bottom of the GUI to display data collected with the suite of waveforms. In this example, the wideband RTI is selected, and the collected radar response is shown. There is a tab for each of the other waveforms and an additional tab for algorithm results. The Features tab includes a dropdown menu of the different discrimination features derived from the collected sensor objects. The available features were based on legacy BMD features and new prototype features derived from Project Hercules or previous R/B games.

Figure 7 depicts a feature/feature plot. The left panel shows the a priori data from a training day scenario while the right panel shows the output from the game-day scenario. The blue teams can select features in real time for the x- and y-axes to explore feature combinations that provide the greatest decision-making utility.

As expected, the a priori data on the left does not match the game-day observations on the right. The blue

2009

DATE: 05/19

DESIGNATION: Joint Advisory Committee (JAC) meeting, 2009

SENSOR SUITE: FB and MC radars, fire control

PURPOSE: First distributed game; blue teams divided and operated different sensors and fire control

2010

DATE: 05/18

DESIGNATION: JAC 2010

SENSOR SUITE: Airborne infrared (ABIR) radar

PURPOSE: Introduced distributed, sensor resource management for two ABIR platforms and Ground-Based Midcourse Defense fire control with no discrimination

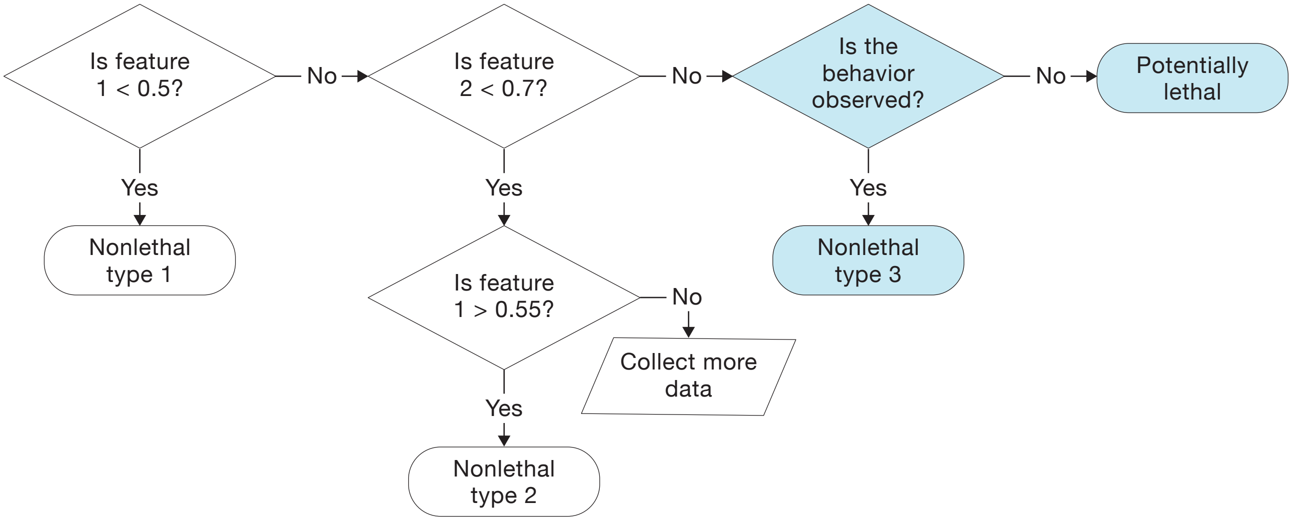


FIGURE 8. This chart represents a portion of a notional blue team discrimination architecture. The blue team used the data provided on training day to identify feature thresholds and determine lethality. During the actual game day, there were off-nominal conditions (i.e., operational or environmental factors were not as planned), and a new feature was used to break a tie from multiple identified lethal objects.

teams must decide how to manage the measurement resources applied to the different objects in order to resolve any uncertainty or ambiguity, and they must interpret the changes in the appearance of the objects that they expected from prior experience. The blue teams faced several questions: Did the red team disguise the reentry vehicle? Was there a deployment malfunction? Are there countermeasures? Are there multiple reentry vehicles? The blue teams could rely on their discrimination architecture logic to request additional sensor resources to resolve the uncertainties.

Figure 8 represents a portion of a discrimination architecture developed in response to the training-day experience. The blue shapes were updated with game-day innovations.

The white team observers kept detailed notes about how each blue team executed its strategy and adapted its decision architecture. To decide which blue team had won, the white team used an overall metric based on lethal objects correctly engaged. If a tie occurred, the white team used tiebreaker metrics, such as the number of objects correctly discriminated, the number of interceptors employed, and resources and time efficiently used. The final out-briefing included a short strategy discussion from each blue team, and the winners were awarded trophies.

Outreach

Over time, the scope of the games broadened to include all aspects of the BMD system of systems. This expansion allowed for the investigation of a wide range of

2011

DATE: 05/17

DESIGNATION: Air and Missile Defense Technology (AMDT) Workshop 2011

SENSOR SUITE: ABIR radar

PURPOSE: Distributed and controlled two ABIR platforms, performed discrimination and passed information to ground fusion center

2012

DATE: 05/15

DESIGNATION: AMDT 2012

SENSOR SUITE: System level

PURPOSE: Eliminated deliberative, planned red scenario. First game with red team being played by game participants and first integrated air and missile defense game. Red team attacks and blue team defends high-value assets (e.g., carrier)

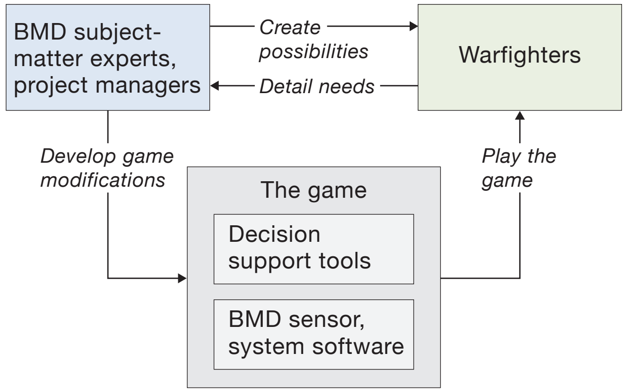


FIGURE 9. The gaming process facilitates interaction between the development community and the warfighter. This graph represents important aspects of interaction between the developer and the user, such as warfighter feedback influencing decision support tools.

potential capability improvements. Figure 9 depicts the important aspects of the interaction between developers and users, and the influence of this intereaction on system technology. The body of blue team participants eventually expanded to include expert BMD analysts and program managers from Lincoln Laboratory, the prime contractors, and the MDA. The warfighter was also brought in during the later phases of game development to help the developers understand not only the challenges faced by the military system operators but also potential future system improvements. The participants provided welcome feedback regarding the GUIs that the Laboratory was developing to display the threat information and decision aids.

In later years, the R/B game was used as an educational tool. The introductory material was transformed into a tutorial on BMD discrimination, and the scenarios were used to enhance understanding of the adversary's capability and the potential of new technology to mitigate the evolving threat. Such games were used in the Lincoln Laboratory BMD Technology Course and played at MD-SEA conferences, the American Institute of Aeronautics and Astronautics BMD conferences, and Lincoln Laboratory's annual Air, Missile, and Maritime Defense Technology Workshop. Participants included employees from MDA, researchers from federally funded research and development centers, warfighters, and prime contractors. At some events, participation exceeded 100 individuals. Graphical user interfaces and decision aids were updated for each subsequent game, and the game focus evolved to address MDA's most pressing issues.

Further Development

As the game was exposed to a broader community, the U.S. Navy took particular interest in its further development. In 2013, the Office of Naval Research established a project to evolve the game into a training tool for Navy operators. The Laboratory and a commercial gaming company, Pipeworks, converted the technology to the standards required for fleet training operations. A detailed discussion of the effort is provided in an article titled "Strike Group Defender" on page 25. Other mission areas at Lincoln Laboratory recognized the advantages of using gameplay to develop and test sensing and decision support technology. An early adopter was the Laboratory's intelligence, surveillance, and reconnaissance program, which developed games specific to that mission area.

The serious games concept and underlying software structures continue to be used in several technical areas. The detailed simulation tools that support algorithm development and the BMD games are still relevant and

2013

DATE: 05/16
DESIGNATION: AMDT 2013
SENSOR SUITE: Electronic warfare (EW)
PURPOSE: Created similar attributes to AMDT 2012 version, with blue team using soft-kill techniques against a red team cruise missile attack

2014

DATE: 06/04
DESIGNATION: AMDT 2014
SENSOR SUITE: EW
PURPOSE: Established game company version of the 2012 game

are continually updated for applications in the various system studies conducted in Lincoln Laboratory's BMD mission area. As the BMDS matures and increases in complexity, it can be anticipated that a new round of BMD games will emerge. ■

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About the Authors

Brian M. Lewis is the leader of the Advanced Undersea Systems and Technology Group at Lincoln Laboratory. He is responsible for managing research and development for a broad range of undersea assessments and technology development efforts. He joined the Laboratory in 2003 as a staff member in the Advanced Concepts and Technology Group and developed advanced radar discrimination algorithms and high-fidelity sensor emulations. In 2008, he moved to the Missile Defense Elements Group and focused on systems analysis and modeling and simulation in the Verification, Validation, and Accreditation program for the MDA's BMDS Sensors Directorate. He has also served as the assistant and associate leader of the BMDS Integration Group, leading the Laboratory's technology development efforts for the Aegis BMD System. He holds a bachelor's degree in mathematics with a concentration in computing from Morehead State University and master's and doctoral degrees in applied mathematics from North Carolina State University. During graduate school, he was employed as a research assistant at Los Alamos National Laboratory and as a member of the technical staff at the Aerospace Corporation.

John A. Tabaczynski joined the technical staff at Lincoln Laboratory in November 1966 after working at NASA's Jet Propulsion Laboratory. Having served as assistant and associate group leader, he became the leader of the BMD Analysis and Systems Group in 1978. In 1984, he was promoted to associate head of the Ballistic Missile Defense Division. His primary technical interests have evolved over the years. Initial tasks involved the application of Kalman filtering techniques to the problem of radar tracking and discrimination. Through the 1970s, he participated in major defense system studies that shaped the evolving BMDS architecture. During this period, he was involved in defining the technology and specifications for the U.S. Army's family of X-band radars. As an outgrowth of this activity, he initiated Laboratory activities in support of the MDA's Sensor Technology Program. In the late 1980s, as manager of the Laboratory's Kwajalein Missile Range Program, he was responsible for conducting the real-time demonstration of BMD technology and algorithms on live missions into Kwajalein. Through the 1990s, he promoted advanced radar technology for BMD applications and co-led an Army BMD study to define the next-generation missile defense radar. This study informed the Laboratory's current program in over-the-horizon radar. In 2000, he worked with staff at the MDA to stand up and execute Project Hercules, a national effort in the development and testing of ballistic missile discrimination technology. In 2004, he was appointed a principal laboratory researcher and continued to work on areas of advanced radar technology. He is currently writing a textbook on advanced radar signal processing for imaging and radar signature modeling. He holds a bachelor's degree from MIT and master's and doctoral degrees in electrical engineering from Purdue University.

2015

DATE: 04/07
DESIGNATION: AMDT 2015
SENSOR SUITE: System level
PURPOSE: Added positioned multiple radars to optimize performance in a raid scenario

2016

DATE: 05/17
DESIGNATION: Air, Missile, and Maritime Defense Technology Workshop 2016
SENSOR SUITE: System level
PURPOSE: Introduced undersea component into 2012 infrastructure