Hardware-in-the-loop Simulations for Ballistic Missile Defense Systems

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Abstract – *It is a major Modeling and Simulation (M&S) effort to develop high fidelity radar simulation test beds to reduce risk by integrating hardware and software, perform system level tests, and verify radar performance in a local facility prior to the integration and test at the radar site. This results in huge savings in resources, time and cost. A summary of various existing hardware-in-the-loop (HIL) simulation tools is provided concentrating on their utilization in performing a large number of radar level performance tests and serving as both a platform for system testing and a software development tool. More emphasis is placed on an innovative high fidelity radar simulation tool known as Radar Digital Signal Injection System (RDSIS) which effectively complements the legacy tools by providing new capabilities required to evaluate advanced radar performance.*

Keywords: Modeling and Simulation, hardware and software integration, Ballistic Missile Defense System, hardware-in-the-loop, cost savings, Radar Digital Signal Injection System

1 Introduction

Modeling and Simulation (M&S) plays a key role in both developing the Ballistic Missile Defense System (BMDS) and assessing its likely effectiveness. Flight tests for missile defense systems in today's environment require substantial time, resources, and expertise. Much more than in earlier missile defense programs, today M&S must be relied upon to account for all pieces of the program, the resources that go into all those pieces, and the integration of the program elements into a single system-of-systems.

Raytheon has developed an approach for the X-band Family of Radars that is extensible to other elements/components in BMDS for end-to-end system-of-systems, including space based systems. Figure 1 depicts a prototype BMDS with all the elements of the system including air, land, and space-based systems.

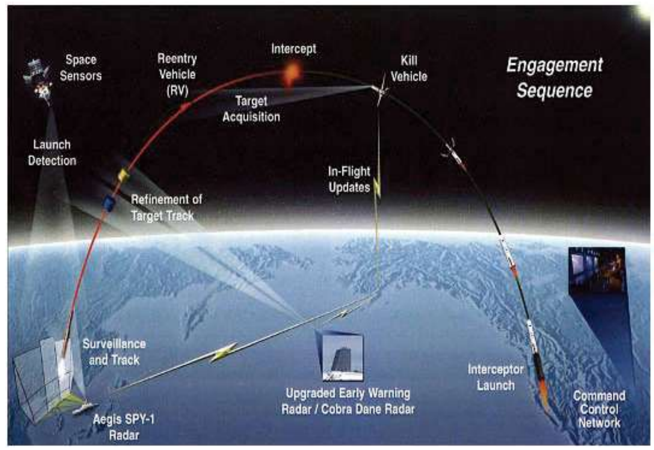

Figure 1. Elements of the Ballistic Missile Defense System.

2 The Ballistic Missile Defense System

Missile defense technology being developed, tested and deployed by the United States is designed to counter ballistic missiles of all ranges—short, medium, intermediate and long. Since ballistic missiles have different ranges, speeds, size and performance characteristics, the BMDS is an integrated, "layered" architecture that provides multiple opportunities to destroy missiles and their warheads before they can reach their targets. The system's architecture includes:

- Networked sensors and ground-based and sea-based radars for target detection and tracking
- Ground-based and sea-based interceptor missiles for destroying a ballistic missile using either the force of a direct collision, called "hit to kill" technology, or an explosive blast fragmentation warhead
- A command and control, battle management, and communications network providing the warfighter with the needed links among the sensors and interceptor missiles.

Testing of the ballistic missile defense system must account for the ever-changing ballistic missile threat and the latest technological developments. An example of the BMDS missile in deployment is shown in Figure 2. Ground and flight tests provide data needed for highly advanced modeling and simulation activities that allow us to measure and predict the performance of all missile defense technologies. Successful flight tests in particular give the warfighter greater confidence in the system's capabilities.

Figure 2. Ballistic Missile Launch.

3 Flight Tests Versus Simulations

Flight tests are critical to understanding BMDS and element performance in a tactical scenario given their high complexity. While flight tests provide a reliable venue for testing new capabilities, they are expensive, may have restrictions and are infrequent. This leads to the following disadvantages of flight tests:

- Flight tests provide only a single instantiation of a particular scenario
- Flight tests do not generate confidence bounds associated with multiple realizations (e.g., as with Monte Carlo simulations) of a particular scenario
- With flight tests, it is not always clear whether performance represents typical or an "outlier" behavior.

On the other hand, simulations, particularly hardware-in-the-loop (HIL) simulations provide huge savings in costs compared to flight tests. In HIL simulations, various hardware tools emulate the corresponding site tools at much lower costs.

HIL is an assembly of key radar hardware elements that emulate the corresponding radar components to achieve similar performance as the radar itself. This simulation capability provides the following advantages:

- Early hardware interconnection and checkout
- Early software interface checkout
- System hardware and software regression testing
- Test bed for integration and test of radar software builds
- Test bed for requirements verification, performance, scenario and Monte Carlo analysis
- Test bed for pre- and post-flight test analysis.

4 Hardware-in-loop Simulations

One of the major M&S efforts is to develop high fidelity radar simulation test beds to accomplish these goals. In this context, several high fidelity radar simulation systems have been recently integrated into the BMDS String Testing Facility (STF) at the Missile Defense Center (MDC) in Woburn, MA.

The BMDS Radar HIL STF is a test resource used to reduce risk by integrating hardware and software, performing system level tests and verifying performance in a local facility prior to the integration and test at the radar site. The STF is a subset of the tactical BMDS Radar system. This subset is sufficient to perform a large number of radar level performance tests and can serve as both a platform for system testing and a software development tool.

Stable low fidelity and simulation test beds already exist such as Digital Simulation (DIGISIM), Analog Simulation (ANASIM) and Capability Release Upgrade Simulation High Fidelity Model (CRUSHM), which have been utilized for many years within BMDS to test the system level performance and capabilities of the BMDS radar, from risk reduction for TOO (Target of Opportunity) mission readiness to root cause determination of operational problems. Each of these three toolsets has particular strengths of simulation capabilities, yet each has limitations versus the real radar operation. Over the years of use, these capabilities and limitations have become well understood. Recently an innovative high fidelity radar simulation tool (a HIL tool) known as Radar Digital Signal Injection System (RDSIS) was added to the repertoire of radar simulation capabilities to help cover some of the existing limitations. Figure 3 provides a pictorial description of the various steps starting from requirements development to integration and testing a newly released radar software in a HIL simulation environment. A block diagram of the corresponding HIL simulation tool RDSIS depicted with various components of the tactical radar is shown in Figure 4.

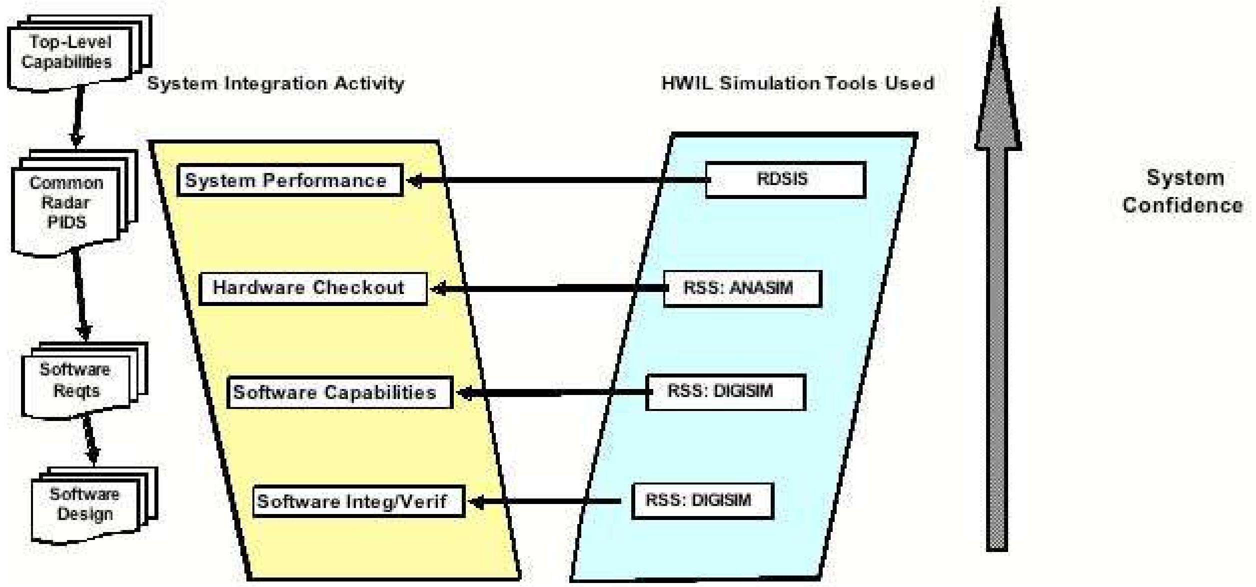

Figure 3. Lifecycle for testing a radar software from requirements to simulation.

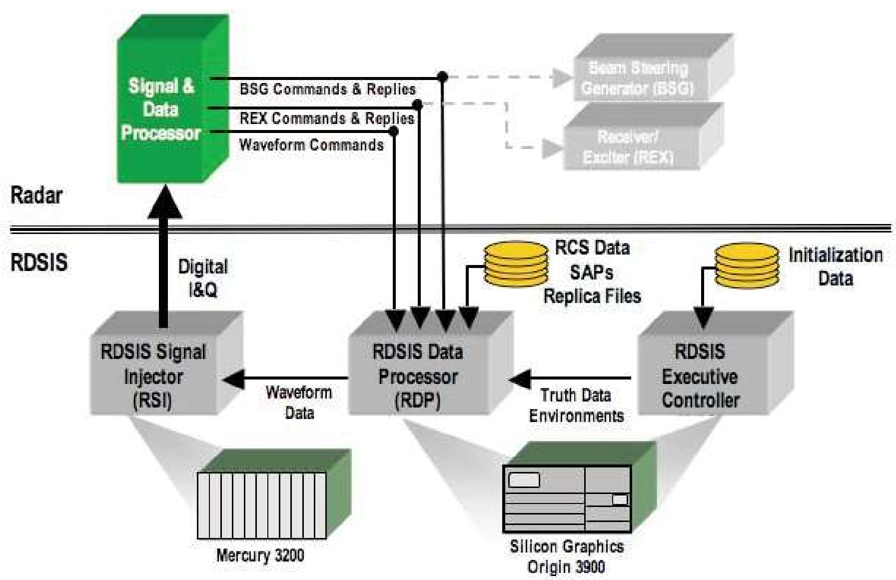

Figure 4. Radar Digital Signal Injection System.

5 Radar Digital Signal Injection System (RDSIS)

The RDSIS is a radar signal simulator/stimulator designed to provide a real-time, high fidelity test capability for the Army/Navy Transportable Radar Surveillance (AN/TPY-2) Radar. The RDSIS simulates In-Phase and Quadrature (I&Q) output from the Receiver/Exciter (REX) and injects these radar returns into the BMDS Radar Signal and Data Processor (S&DP) HIL environment.

This unique approach provides a test capability to exercise the complete signal and data processing functionality, from beginning to end, in a real-time, tactical configuration. This capability also allows simulation of detailed effects on the radar return signals that may affect advanced radar processing algorithms. The RDSIS simulates radar return data for targets, associated objects, launch and separation debris, and man-made and natural environments.

The major components of the RDSIS are the RDSIS Executive Controller (REC), RDSIS Data Processor (RDP), the RDSIS Signal Injector (RSI), and Participant Interface (PI). RDSIS consists of three primary software configuration items and two primary hardware configuration items. An SGI 3000-series multiprocessor computer performs control functions and supports data processing on radar actions.

The REC provides initialization and scenario truth during testing. The REC is the overall execution and control mechanism of the RDSIS. In particular, the REC loads, activates and controls all initialization parameters with primary responsibility to provide the user interface, manage threat object data injection, record threat data, and provide overall RDSIS operational status.

Once an action command is received from the radar's S&DP, the RDP module computes the required parameters of the signal to be injected into the S&DP. This information is passed to a special-purpose computer, which consists of multiple digital signal processing (DSP) boards that execute the RSI software module. The RDP interfaces to the AN/TPY-2 Radar S&DP for processing REX, Beam Steering Generator (BSG), and waveform SPS commands. The RDSIS generates status reply messages as requested by the AN/TPY-2 Radar. The RDP generates waveform return data based on the commanded waveform. The waveform return data is provided to the RSI, which generates I&Q data for injection into the AN/TPY-2 Radar S&DP during the appropriate resource period scheduled by the radar.

The RSI produces the sampled digital signal that simulates the output of the radar's REX. This time-sampled, baseband signal is supplied to the S&DP through packet digital communications, which closes the control loop with the radar's scheduling and control software. The RSI is a multi-processor computer system. The RSI includes processing modules where each processing module houses processors and Random Access Memory (RAM). The RSI includes fiber optic data link cards and an Inter-Range Instrumentation Group (IRIG) time signal cPCI card. The RSI includes a single board computer running the Solaris operation system and the Mercury Multi-Computer Operating Environment (MCOE).

RDSIS is the basis for several future capabilities, including simulation-over-live testing for the Theater High Altitude Air Defense (THAAD) program and Concurrent Test Training and Operations (CTTO) for the full-up BMDS system. The RDSIS will enable the BMDS CTTO to operate the tactical software in the deployed system and could allow the system to be tested while maintaining tactical operations. Using an RDSIS to stimulate a back-up computer string at a tactical site allows tactical software upgrades to be tested in a system-wide context prior to the software being loaded into the deployed operational system.

RDSIS simulates the I&Q output from the Receiver/Exciter (REX) and injects these signals into the S&DP. The fidelity of these I&Q samples is measured by the accuracy of the radar observables, calculated by the S&DP using these I&Q samples. These radar measurements are intended to support the major radar functionalities such as detection, tracking and discrimination. This approach provides a test capability to exercise the complete signal and data processing functionality in a real-time tactical configuration by simulating radar return data for targets, associated objects, launch and intercept debris, and man-made and natural environments.

During test exercises (ground and flight) the RDSIS enables the AN/TPY-2 radar to participate through the PI SI. RDSIS only utilizes the PI to interface with the Single Stimulation Framework (SSF) Interface Unit (SIU), formerly known as the Missile Defense Exerciser System (MDSE), for processing truth data. During a distributed simulation, the Test Execution Controller (TEC) communicates with each participating Segment SIU. The TEC passes scenario data to the SIUs and receives initialization and status information from the SIUs. A generic RDSIS system is shown in Figure 4 and related information can be found in the references [1-4].

Operation of the RDSIS is determinant upon operating live events in stand-alone mode (where there is direct human interaction within the MDC STF) or live missions with the TEC. As new radar implementations are made, these implementations are scaled as new software release builds to the RDSIS to ensure compatibility and functionality for requirements being tested and investigated.

This cutting edge Radar Analysis Technology is essential to the continuation of Raytheon Company Systems Engineering total systems solution approach. Figure 5 shows an AN/TPY-2 which is fielded at site. Previously designated as the Forward Based X-Band Transportable (FBX-T) Radar, this X-band frequency radar is capable of tracking all classes of ballistic missiles and identifying small objects at long distances. This radar plays a vital role in the BMDS by acting as advanced "eyes" for the system, detecting ballistic missiles early in their flight and providing precise tracking information for use by the system. Use of multiple sensors provides overlapping sensor coverage, expands the BMDS battle space, and complicates an enemy's ability to penetrate the defense system. The same radar with different software provides surveillance and fire control support for the Terminal THAAD weapon system. The AN/TPY-2 is a high-power, transportable X-Band radar designed to detect, track and discriminate ballistic missile threats.

Figure 5. AN/TPY-2 Radar.

6 Conclusions

Hardware-in-the-loop simulation provides huge savings in cost compared to testing the radar at site. The advantages of the radar simulation tools that are being used to achieve the performance required to emulate flight tests have been presented. Among the simulation tools, the advantages of an innovative high fidelity simulation tool known as RDSIS are also presented.

Acknowledgment

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