Standard Missile-2 Block IVA Analysis and Test

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Standard Missile-2 Block IVA is being developed to provide a Theater Ballistic Missile Defense capability for the Navy. The need to achieve high lethality against tactical ballistic missile threats has dictated a Block IVA missile configuration embodying low guidance noise, rapid missile response time, and a forward-looking fuze concept. As Technical Direction Agent to the Navy for Standard Missile, APL provided top-level requirements for the Block IVA Program and continues to provide an independent assessment of the Block IVA design through analysis, simulation, and testing. Three specific areas of APL involvement exemplify contributions to the Block IVA Program: (1) system-level simulation and analysis, (2) guidance section hardware and software testing, and (3) infrared seeker dome testing. Improvements developed as a result of these systems engineering activities are key to ensuring that the Block IVA design meets its overall system requirements.

INTRODUCTION

The Standard Missile-2 (SM-2) Block IVA design will provide the Navy Surface Fleet with a Theater Ballistic Missile Defense (TBMD) capability while retaining capability against anti-air warfare cruise missile threats. Aegis ships equipped with Block IVA rounds and associated Aegis Weapon System radar and processing system upgrades will provide defense of debarkation ports, critical coastal assets, and population centers against short- and intermediate-range tactical ballistic missiles.

The Block IVA missile, which will intercept the threat under endo-atmospheric conditions, involves evolutionary changes to the existing Block IV anti-air warfare design. The need to achieve high lethality against tactical ballistic missile threats has dictated a Block IVA configuration that embodies low guidance noise and rapid missile response, as well as a forward-looking fuzing concept that can place missile warhead fragments on the desired vulnerable area of a high-speed tactical ballistic missile threat. For these characteristics to be achieved, the Block IVA guidance section includes a new side-mounted imaging infrared (IR) seeker that provides low-noise target centroid angle measurements for guidance and information for calculating the warhead fuzing solution. The design also includes a new forward-looking active radio-frequency (RF) adjunct sensor (RFAS) that provides additional measurements that are required for fuzing. Other guidance section improvements include an upgraded digital signal processor to provide adequate computing throughput for a new highly responsive multivariable autopilot, an improved terminal guidance algorithm, and the fuzing algorithm. The Block IVA missile is being developed by Raytheon Company under sponsorship of the Navy Program Executive Office, Theater Surface Combatants (PEO (TSC)).

For intercepts against tactical ballistic missile threats, the Block IVA missile is command-guided (via an uplink from the Aegis ship) during the early part of its flight. As the missile approaches the target, the ship supplies designation information that the missile uses to point its IR seeker toward the target. The missile initiates IR track and terminal guidance on the designated object, with the IR seeker providing target state measurements for use in an optimal guidance law. As the missile continues to close on the target, the missile-to-target range eventually becomes small enough that the target image is resolved (i.e., covers multiple focal plane pixels) in the IR sensor field of view. At about the same time, the RFAS is also pointed at the target and begins to provide target information. These IR and RFAS data are used in a forward-looking fuze (FLF) process to determine the location of the target payload relative to the interceptor missile warhead. The missile uses this payload location estimate to compute the burst time required to cause the Block IVA warhead fragments to strike the target payload (in the event that body-to-body impact of the target is not achieved).

As SM Technical Direction Agent for the Navy, APL is providing an independent assessment of the Block IVA design from a systems engineering perspective. In this role, APL provided requirements definition as well as preliminary design concept development and evaluation early in the Block IVA Program. As the design matured, APL efforts shifted to evaluation of the contractor's detailed design. These design evaluations involve high-fidelity simulation studies and complementary analysis efforts as well as hardware and software testing.

Much of the focus of these efforts is on evaluating the operation of the Block IVA design as an overall system, providing confidence that all elements of the missile guidance, control, navigation, and fuzing subsystems operate in the manner required to allow the missile to defeat the tactical ballistic missile threat. APL's high-fidelity Block IVA system simulation, which models all of the missile sensors, the associated processing algorithms, and ship system interfaces, is used to ensure that the functional design meets its requirements. Testing in the APL Guidance System Evaluation Laboratory (GSEL) provides confidence in these simulation results by ensuring that the integrated hardware and software designs, as implemented in the actual missile guidance section, not only meet their design requirements but also will operate as desired in off-nominal and contingency environments. In addition, early design studies indicated that survival of the side-mounted IR seeker dome in the high-velocity (and hence, high aerothermal heating) environment associated with Block IVA flight was a potential risk area for the program. Hence, APL initiated analysis and test activities to quantify the IR dome aerothermal environment, to relate these thermal characteristics to the dome survival margin, and to verify the analysis through wind tunnel testing of prototype dome assemblies. Examples from these analysis and test activities are described in the remainder of this article.

SYSTEM MODELING AND SIMULATION ANALYSIS

APL has a long heritage of contributions in the area of SM simulation development and analysis, beginning in the mid-1960s with simplified analog models of the SM-1 Block V design. As computer and workstation processing speeds increased, more capable all-digital simulations were developed, leading to a high-fidelity, stochastic, six-degree-of-freedom (6-DOF) simulation of the SM-2 Block IV missile in the late 1980s. This simulation included highly detailed models of the fast Fourier transform–based missile receiver and radar data processing as well as a high-fidelity model of the low-altitude multipath environment. The family of APL SM simulations is maintained in a classified workstation environment and controlled under rigorous configuration management procedures.

Early Navy TBMD concept definition studies were performed in the mid-1990s using a modified version of the Block IV 6-DOF simulation. An IR seeker model, developed under the High Performance IR Seeker Program, was integrated into the simulation along with other guidance and control modifications to support early design studies. This simulation also served as the basis for a representation of the Block IVA Risk Reduction Flight Demonstration (RRFD) missile configuration. The RRFD Program demonstrated the feasibility of using the Block IVA IR seeker for TBMD missions by conducting a successful intercept of a Lance tactical ballistic missile target at White Sands Missile Range (WSMR) in January 1997.

Eventually, the Block IV/IVA simulation was split into two independent simulations to facilitate efficient development of both variants. The Block IV models common to the Block IVA configuration were retained along with Block IVA–specific models. Selected subsystem models developed, verified, and validated as part of the RRFD Program were then integrated into the Block IVA version of the simulation to create an official Block IVA 6-DOF simulation. Upgrades were subsequently made to enhance the detailed modeling of the tactical ballistic missile target kinematics and signatures (both IR and RF), the IR seeker platform and sensor, the RFAS sensor, the Aegis SPY-1 radar and weapon control system (including the target designation process), and the FLF algorithm. An interface to a high-fidelity image-based model of the Block IVA IR seeker was also included. (The image-based seeker simulation is discussed in detail in Steinberg et al., this issue.) Although the existing APL Block IVA simulation includes key elements of the Aegis Weapon System (including launch scheduling, midcourse guidance, missile/target track filtering, and uplink/downlink operation), efforts are also under way to integrate the missile 6-DOF simulation model into a comprehensive Area TBMD system simulation that includes a detailed SPY-1 FirmTrack model and representations of other weapon system functions.

The Block IVA simulation model has been a critical tool in numerous Block IVA studies performed by APL, starting with the development of Block IVA requirements and continuing with evaluations of the contractor's guidance, autopilot, and fuzing designs. Several examples of such studies are discussed in the following sections.

Top-Level Requirements Development

APL performed early Block IVA simulation studies to support the development of the Block IVA Top Level Requirements (TLR) document. The TLR specified the requirements against which the Block IVA missile was to be designed and evaluated. A fundamental requirement for the system is the defended footprint, which is the area on the surface of the Earth to be defended by the Block IVA missile. The defended footprint is defined in terms of maximum downrange, crossrange, and backrange target impact points for which the Block IVA missile must provide intercept capability. The missile is required to provide at least a minimum average probability of kill (P_K) for intercepts above this defended footprint. APL was instrumental in defining the engagement space requirements over which this P_K requirement must be satisfied.

In defining the engagement space requirement, APL worked to strike an acceptable balance between missile and shipboard system performance requirements. From an overall Area TBMD system standpoint (i.e., including both Block IVA missile and Aegis ship system performance), the fundamental top-level requirement is probability of negation (P_N). P_N is a function of both the probability that the Aegis Weapon System provides engagement support (P_{ES}) and the probability that the interceptor kills the target, given the Aegis system support (P_K). Furthermore, P_K is a function of the target intercept altitude. Hence, the engagement space requirement is determined by specifying the performance of the missile as a function of altitude (i.e., (P_K(alt)) and specifying the probability density function of allowable intercept points (i.e., pdf(alt)). The mean intercept altitude (as a function of the intercept downrange) is dictated by the Aegis launch scheduling policy, with the launch scheduler designed to ensure that P_K is maximized.

Although the distribution of intercept altitudes (i.e., the engagement space requirement) reflects a trade-off between missile and ship system performance requirements, this distribution is almost entirely controlled by the accuracy with which the ship can schedule launches. If variations in intercept altitude are to be kept low, the target must be in track for a fairly long time to ensure that the SPY track filter process has settled before the target track is used in the missile launch scheduling process. The need for a long prelaunch target track time would result in a requirement for a high level of ship radar resources to support any given engagement. On the other hand, if limited ship resources dictate a shorter prelaunch track time and hence a broader intercept altitude distribution, the missile must have good performance over a wide range of intercept altitudes and hence over a wide range of intercept conditions (i.e., velocity, dynamic pressure, and target IR intensity).

To determine the proper balance between ship and missile constraints, APL conducted a covariance analysis to relate the distribution of intercept altitudes to the length of the ship radar track settling time. The length of the required track settling time is directly related to the acquisition range of the radar. An example result is shown in Fig. 1, which plots the standard deviation of altitude variations σ_{alt} for various radar settling times. To verify the results of this covariance analysis, the Block IVA 6-DOF simulation was used to investigate the intercept altitude distribution at the maximum required downrange impact point. Target acquisition by the ship radar was forced to occur at the appropriate time to allow the desired amount of track settling before the interceptor launch was scheduled. A set of 200 Monte Carlo simulation runs was performed. The distribution computed through this 6-DOF simulation study was nearly the same as that predicted by the covariance analysis. In addition, the 6-DOF simulation was used to estimate the missile P_K as a function of altitude, i.e., P_K(alt).

APL used parametric distribution data similar to those shown in Fig. 1, along with missile P_K(alt) data, to negotiate an engagement space requirement that was acceptable to both the ship and missile design agents (Lockheed Martin and Raytheon, respectively). The agreed-upon requirements were documented in the TLR as functions of target range and impact point and are an integral part of the Block IVA defended footprint calculation process.

Autopilot Evaluations

For early requirement studies such as the one described in the previous section, the APL simulation included only a simplified version of the Block IVA autopilot (based on required response times). However, the Laboratory also evaluated the detailed Block IVA autopilot

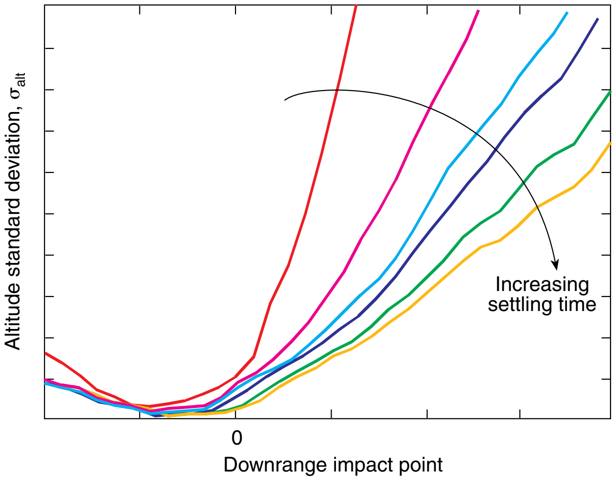

Figure 1. Computed Block IVA intercept altitude dispersion as a function of SPY radar track settling time and downrange impact point. The data indicate that intercept altitude variations are reduced as track settling times increase.

design subsequently developed by Raytheon. The missile autopilot ensures that the aerodynamic forces on the missile cause it to follow the lateral acceleration commands computed by the missile guidance system. Deflection commands to the tail fins (actuators) result in rotational moments being applied to the airframe, which in turn cause the missile body to rotate relative to its velocity vector. This angle of attack between the missile airframe and the velocity vector produces lateral accelerations. The autopilot design must make certain that the commanded accelerations are achieved quickly in response to changing guidance commands (i.e., meeting response time requirements) while still maintaining stability in the presence of uncertainty in the knowledge of actuator, inertial instrument, and aerodynamic characteristics (i.e., meeting stability margin requirements). The autopilot meets these design goals through an implementation that involves (1) the measurement of missile body rotational rates and accelerations by the inertial instruments and (2) the compensation of the rate and acceleration estimates via feedback gains that vary with flight condition (missile velocity, altitude, mass properties, and angle of attack). To meet the response time and margin requirements over the full extent of the missile engagement space, the autopilot designer selects individual sets of gains corresponding to the thousands of different possible flight condition combinations.

APL conducted two general types of autopilot evaluations to ensure that the Block IVA autopilot met its specified performance objectives. Linear control system analysis techniques were used to obtain a measure of missile response time at flight conditions spanning the design space (Fig. 2). Gain and phase stability margins were also computed via linear analysis techniques through characterization of the open-loop frequency response of the autopilot design. The results were summarized in terms of statistical distributions of performance over the flight envelope. APL also extensively investigated missile autopilot performance by exercising the Block IVA 6-DOF simulation. In contrast to the linear analysis results, the 6-DOF simulation yields nonlinear measures of autopilot performance that include the effect of missile acceleration limiting, actuator rate limits, and angle of attack–dependent variations in airframe properties that are not readily captured through linear analyses. During these 6-DOF simulation evaluations, missile lateral acceleration and fin position and rate responses were examined for any evidence of control system instability. Achieved lateral accelerations were also compared to the autopilot commands for complex maneuver command inputs. The combination of linear and nonlinear autopilot analyses performed by APL pointed to areas of the design that required refinement (confirming Raytheon results) and thereby helped to ensure that the Block IVA autopilot design would meet its performance requirements.

Forward-Looking Fuze Evaluations

A critical new feature of the Block IVA design is the FLF. To analyze the capabilities of the Raytheon FLF design, APL developed a detailed model of both the FLF algorithms and the IR and RFAS sensors that provide data for the warhead burst time calculations. The RFAS modeling was particularly challenging because of the need to accurately represent the computationally intensive signal processing that is part of the actual flight code while still maintaining a model that is consistent with 6-DOF simulation throughput constraints. To model this complex process in a way that is computationally efficient enough to be used in the APL 6-DOF simulation, elements of the RFAS response are computed from an analytical closed-form solution. The approach used also requires a target radar cross section (RCS) representation that models the distinct radar scatterers associated with the target vehicle. Such models were developed by the Naval Air Warfare Center, based on processing of test target vehicle RCS measurements using inverse synthetic aperture radar techniques.

The high-fidelity RFAS model in combination with the target RCS models were used to investigate the ability of the RFAS to provide accurate target measurements. 6-DOF simulation runs indicate that the measurement accuracy becomes increasingly better as the RFAS transitions through its various processing modes. Similar studies were performed to assess RFAS accuracy for sensor characteristics representative of early proof-of-design hardware. These later studies, which modeled the characteristics of the actual early developmental hardware, pointed to areas where design improvements were warranted. Accordingly, Raytheon introduced enhancements into the RFAS design to

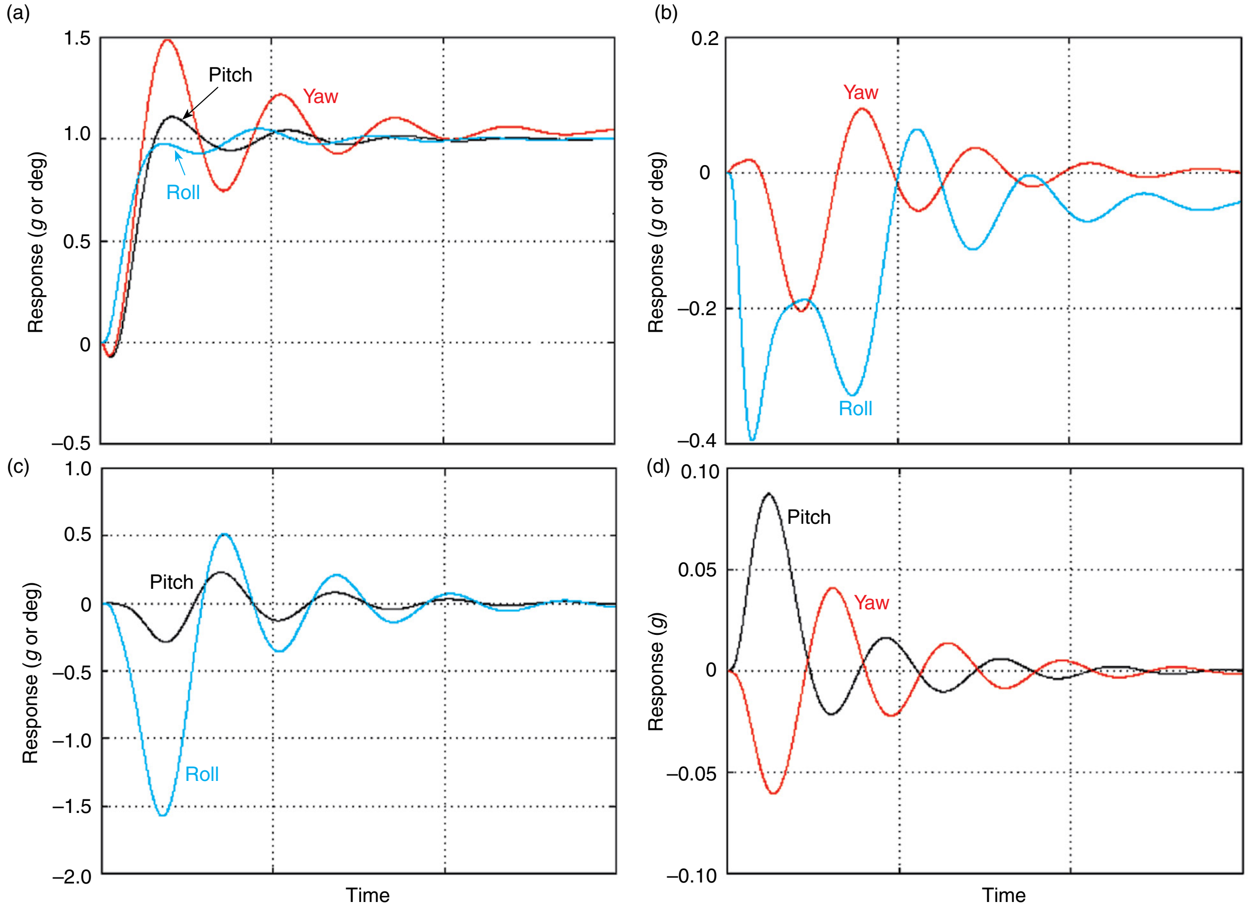

Figure 2. Notional time response results from linear autopilot analysis studies. (a) In-channel responses to pitch, yaw, and roll step inputs. Cross-channel coupling that results from (b) 1-*g* pitch step, (c) 1-*g* yaw step, and (d) 1° roll step.

ensure that the final hardware design would support FLF performance requirements.

System-Level Performance Evaluations

As the Block IVA design has matured, the models contained within the APL Block IVA 6-DOF simulation continue to be refined to ensure that they are accurate representations of the final Block IVA flight hardware and software. Confidence in the models is being enhanced by verifying the APL simulation against results from an independently developed simulation at Raytheon. This simulation verification process is being conducted in phases. The initial phase involved comparisons prior to Block IVA control test vehicle (CTV) missions that were successfully conducted at WSMR during the summer of 2000. Confidence in the APL simulation was further strengthened through validation comparisons to the CTV flight telemetry data. The resulting simulation was used to conduct an extensive evaluation of Block IVA performance relative to the TLR specifications. This study, completed in February 2001, was performed to ensure that the Raytheon design met its specifications, to evaluate risk areas, and to identify any areas where design refinements might be appropriate. The study evaluated P_K and other Block IVA performance metrics within and beyond the required defended footprint and engagement space regions. The associated 6-DOF simulation included wind tunnel–derived aerodynamics data; models of the guidance, autopilot, navigation, and fuzing algorithms that closely represent the actual flight software; and the detailed RFAS model described previously. The extensive nature of the study uncovered a number of areas where design refinements might be considered. Such large-scale performance evaluation studies will be repeated periodically throughout the Block IVA Program, culminating in a study using the APL Block IVA simulation after it has been validated against data from the full set of WSMR and at-sea flight tests.

GUIDANCE SECTION HARDWARE AND SOFTWARE EVALUATION

Although the APL 6-DOF simulation includes extensive models of the various Block IVA subsystems, full evaluation of the Block IVA design must include assessment of the hardware and software as actually implemented into the missile. Since 1964, APL has evaluated SM guidance section hardware and software in the GSEL. (General GSEL capabilities, including future upgrades to the facility beyond those summarized in this article, are described by Marcotte et al., this issue.) APL GSEL evaluations have historically assessed the hardware differently from the way it is done at corresponding design agent facilities. The design agent typically evaluates the design against its documented flowed-down requirements. APL, on the other hand, also evaluates the performance of the integrated hardware and software design in a variety of "what-if" situations. For example, during GSEL testing performed prior to the Block IVA RRFD guided flight test, APL determined that an unexpected transient in the estimated time-to-go information could cause the IR seeker to attempt target acquisition before the IR dome cover was ejected. This problem was subsequently corrected in the flight software prior to the successful flight test. Hence, GSEL testing complements tests being performed at design agent facilities.

For the Block IVA Program, GSEL testing of the Block IVA guidance section is providing an independent evaluation of the Block IVA RF semi-active seeker, RFAS, IR sensor, and associated signal processing functions. These tests address verification of the overall integrated system, including proper operation and timing in both clear and countermeasures environments. With the addition of the new IR seeker and RFAS into the Block IVA configuration, the evaluations are focusing on assessment of IR acquisition, target designation and handover logic, IR track and guidance, and FLF. During initial Block IVA Program testing, the IR seeker has been removed from the remainder of the guidance section and mounted on a separate optical bench located in conjunction with an IR source. This configuration allows the IR seeker to be tested either independently or while electrically connected to the remainder of the guidance section (across a digital interface) for combined RF/IR testing. In the latter case, the motions of the RF and IR sources (i.e., target motions) are synchronized so that the system simulates the RF and IR input that would be seen from a single target and presented to an integrated guidance section.

The FLF function and associated RFAS sensor are unique to the Block IVA design, resulting in the need to develop a new RFAS target generator for GSEL Block IVA testing. The RFAS target generator simulates the target return received by the RFAS during an intercept engagement. The target generator sends a sequence of electrical inputs to the guidance section under test; those signals are based on a precomputed table of endgame parameters from the APL Block IVA 6-DOF simulation. The parameters sent are functions of the target length and aspect. The GSEL host computer initiates "playback" of the scripts at the appropriate time during the test run. Interface logic detects the RFAS carrier frequency and the time of radar transmission from the guidance section. When the transmit signal is detected, dedicated interface logic uses the table output to determine in real time the appropriate instantaneous RF target return signal characteristics. The missile frequency reference is provided to the RFAS target generator system to ensure a common reference, thus achieving an accurate simulation of the radar return.

GSEL testing for the Block IVA Program also includes evaluation of the new IR seeker. Two IR scene simulators are available to optically project calibrated IR scenes to the seeker under test. Stand-alone IR tests can use either of these simulators, which are the Infrared Environment Simulator (IRES) (used in previous RRFD testing) and the new Thermal Picture Synthesizer (TPS). The IRES can simulate an expanding, moving target imposed on a background that represents the heated IR dome. Target size can be dynamically varied from an unresolved image to one that covers the maximum extent of an approaching target in the IR seeker field of view. The target aperture is back-illuminated with a calibrated blackbody source that ranges from 50° to 1000°C. The background is illuminated with an extended area blackbody source that ranges from ambient to 600°C. A pair of matched, variable-attenuating wheels is used to allow the background to be rapidly ramped up in radiance. The wheels are counter-rotated to maintain a spatially uniform background that dynamically changes the background temperature to simulate the heating of the seeker dome during flight.

The TPS (Fig. 3) is a 256 × 256 calibrated thermal resistor array with an apparent pixel temperature range

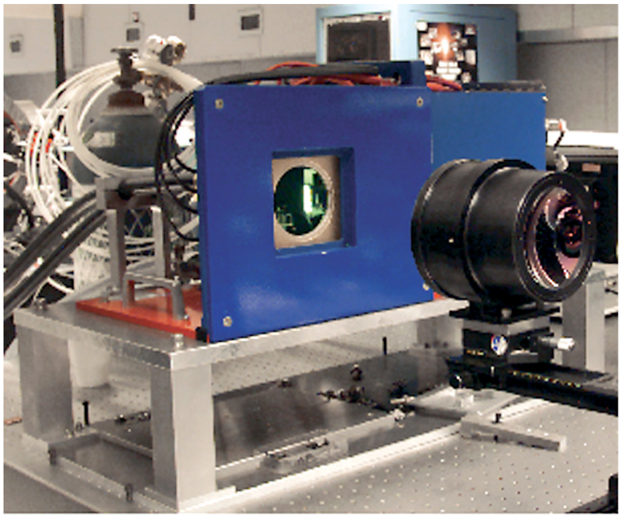

Figure 3. The IR seeker scene simulators, which consist of the TPS and IRES. The resistor array of the TPS is behind the circular window in the center of the blue box.

from ambient to 200°C. The TPS can be controlled through two separate means. When controlled via the parallel port of a PC, the TPS provides output at several frames per second. This capability is useful for testing with static scenes or slowly changing sequences. The second control approach involves a real-time image sequencer that provides the capability for playing a predefined image sequence into the TPS at full frame rate, allowing detailed modeling of the target and scene (though with the restriction of using scripted files from the 6-DOF simulation). There is also a provision for synchronizing the TPS frame rate with the IR seeker frame rate to eliminate image sampling problems. Figure 4 is an image from the RRFD flight as presented to a mid-wave IR camera by the TPS. The IRES and TPS images can also be combined, with the TPS scene folded into the IRES path to allow the TPS to generate the target scene and the IRES to generate the background and to provide scene motion.

Stand-alone IR seeker tests for the Block IVA Program are evaluating a range of IR requirements. Sensor tests include measurement of seeker noise, responsivity, resolution, and other basic seeker performance measures. Acquisition and tracking tests are assessing performance for simple static and dynamic scenes as well as for ramping backgrounds that simulate the heating of the seeker dome during flight. Platform tests are being performed to assess body motion coupling, drift, servo step response, and pointing accuracy performance. Tests with background include cases with clutter (debris from the target in the field of view), stray radiation (from the Sun or the missile forebody), a warhead burst from an earlier intercept in the field of view, and other stressing backgrounds. Tests are also being performed for various off-nominal cases, including stressing debris scenes, higher-than-expected radiance from the hot seeker dome, and excessive blur (as might be caused by unexpected aero-optical or aero-thermal effects or by motion smearing).

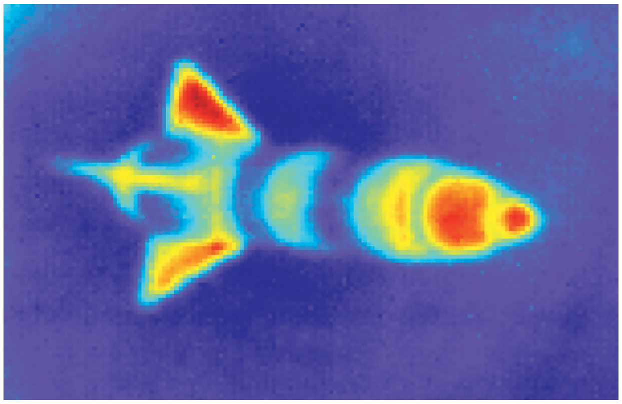

Figure 4. A target image as displayed by the TPS and captured by a mid-wave IR camera.

In addition to these stand-alone seeker tests, GSEL testing also includes evaluation of the IR seeker and RFAS as part of the overall guidance section. During these dual-mode tests, the missile guidance section itself controls the IR seeker, generating all commands required to apply power to the seeker and have it acquire and track the target. Figure 5 is a block diagram of the test configuration for dual-mode FLF evaluations. For these evaluations, the GSEL test inputs are generally obtained from scripts based on 6-DOF simulation runs, with the IRES, TPS, and RFAS target generator all synchronized through the GSEL host computer. The scripts include IR target information, RF target information, RFAS inputs, inertial instrument output (missile state dynamics), and ship uplink data.

The FLF and other dual-mode GSEL tests emphasize demonstration of functionality in those areas that are new for the Block IVA design. Consequently, a majority of the evaluations are focusing on post-midcourse guidance functionality, with lesser emphasis being placed on the earlier portions of flight (during which operation is similar to that in the previous Block IV design). Overall dual-mode GSEL test objectives include the evaluation of performance sensitivity to various FLF inputs, verification of 6-DOF simulation models, and investigation of robustness to off-nominal conditions, with an emphasis on sensor fusion performance. Specific areas of focus include IR seeker discrimination and designation, IR seeker trackpoint processing, accurate measurement of target information by the RFAS, and the ability to combine the IR seeker and RFAS data for the fuzing solution. Contingency situations that are being addressed include (but are not limited to) scenarios where either the RF or IR target is not acquired or is lost at some point after acquisition, acquisition is delayed, or significant errors exist in the uplink information.

As an indication of the type of testing that is being conducted during the Block IVA Program, consider one particular test that was performed in the GSEL during the previous RRFD Program. A primary concern during the RRFD IR guided flight was the effect of dome heating–induced radiation on the received target signal. The impact of such heating was investigated by simulating dome heating using the IRES variable attenuator wheels. During the test, the seeker was commanded to track a static target, and the attenuator wheels were programmed to present a heating background to the seeker. The lower part of Fig. 6 shows the increase in the average background as measured by the seeker. The received target signal is plotted in the upper part of the figure. Although the post-processed target signal dropped slightly during the background ramp-up, by the end of the test (with the hottest scene) the target signal had returned to essentially the initial signal level. Hence, despite a

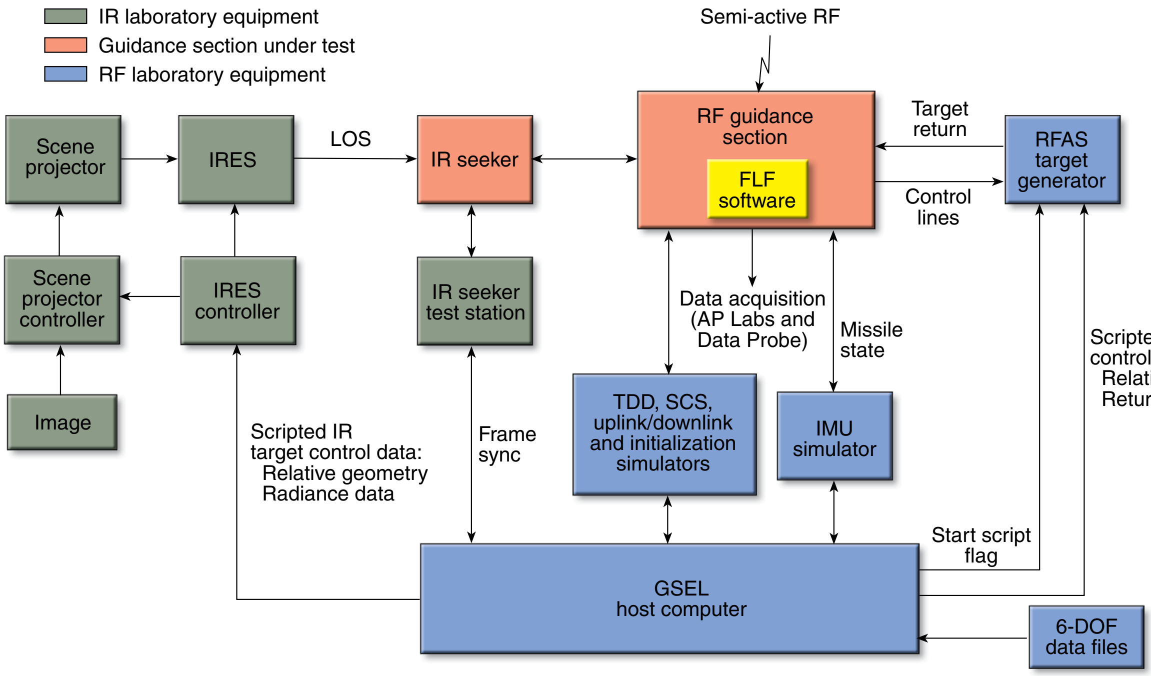

Figure 5. Diagram of the APL dual-mode GSEL test configuration, showing the coordinated control of both the IR seeker scene simulators (the IRES and TPS scene projector) and the RFAS target generator. (IMU = inertial measurement unit, LOS = line of sight, SCS = steering control section, TDD = target detection device.)

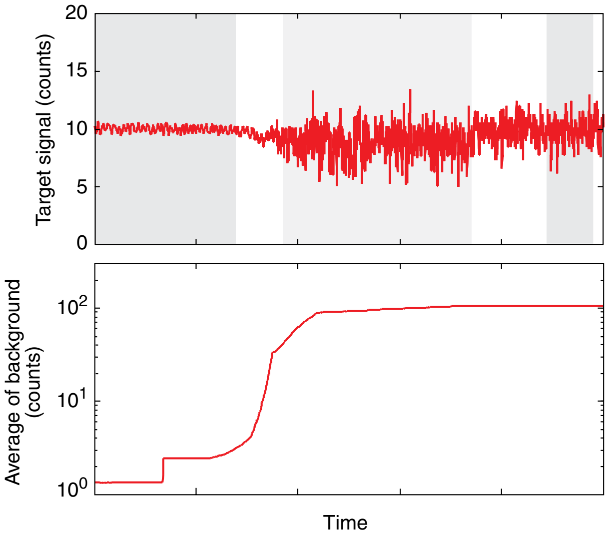

Figure 6. IR target tracking results with a ramping hot-dome background. The lower part of the figure shows the increase in the average background versus time. The upper part shows that the peak target signal varies only slightly despite the significant increase in background level.

100-fold increase in the background radiation, the average target signal showed little variation.

IR DOME TESTING

While GSEL testing (supplemented by 6-DOF simulation analysis) evaluates the functionality of the integrated hardware and software designs relative to their requirements, it is not able to address survival of the sapphire IR dome in the presence of the thermal stresses created in the high-velocity Block IVA flight environment. This area has been addressed via aerothermal and structural analyses, which were in turn validated through wind tunnel testing.

Prior to the actual start of the Block IVA Program, APL played a major role in developing the enabling technologies for the IR seeker dome. The dome, side-mounted about 1 m downstream from the nose, interacts with the airflow to generate complex shock and flowfield patterns that are unique functions of the missile speed, angle of attack, altitude, and external dome cooling gas mass flow rate. Figure 7 shows the uncooled dome flow field as visualized during tests conducted in the APL Avery Advanced Technology Development Laboratory Cell 4 wind tunnel. The full-scale dome was tested on a shortened forebody to produce the representative flow interactions that most greatly influence the dome thermostructural response. High aerothermal heating occurs near the intersection of the boundary layer separation shock and the dome bow shock. Without a thermal protection system, these heating patterns could generate asymmetric temperature distributions that elevate material stresses beyond the sapphire strength limits, causing a brittle fracture of the dome.

Initial exploratory testing in the APL Cell 4 wind tunnel examined nine dome heat flux reduction techniques. Passive techniques that use upstream protuberances to lower the surface heating gradients and

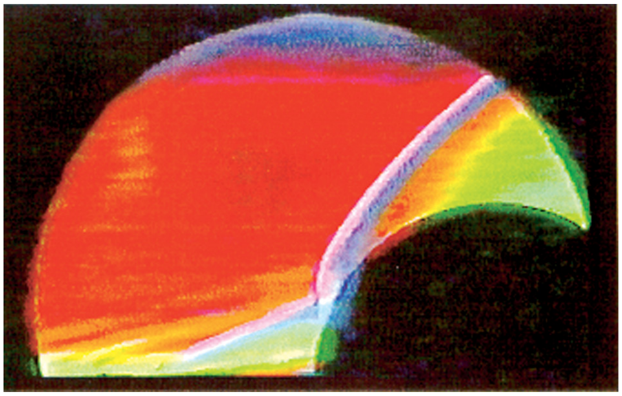

Figure 7. Flow-field structure over an uncooled IR dome as seen during APL wind tunnel tests. The peak dome heating is located near the interaction between the separation shock and the dome bow shock.

approaches that use coolant gas injected in front of the dome were considered. Concerns about the protuberances providing sufficient protection over the entire flight operational envelope and the fact that they may cause undesirable IR sources led to pursuit of the active dome cooling design as the baseline for the Block IVA configuration. The effectiveness of argon, helium, and nitrogen coolant gases was studied. Argon was selected because it provides the largest coolant mass that can be stored at high pressure for extended periods of time in the missile. Figure 8 shows how the placement of the coolant injector slot affects the heat flux along the dome centerline, where the elevation angle is measured from the forebody surface. The uncooled peak heat flux is used to normalize the data, and the uncooled heating distribution is shown as the baseline condition. By injecting coolant upstream of the dome, the heat flux and resulting temperature gradients are significantly reduced, lowering the risk of dome failure. The placement of the upstream coolant slot for zero angle-of-attack conditions was determined from these APL exploratory wind tunnel testing studies and associated analyses.

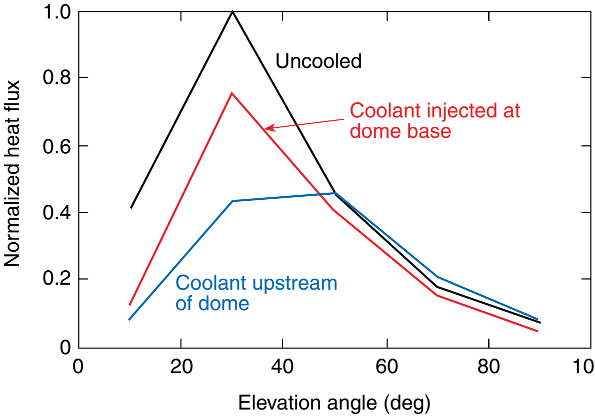

Figure 8. Effect of location of the IR dome cooling system injector slot on dome heating. Locating the coolant slots forward of the dome resulted in a reduction in peak heating levels.

Because the missile is not confined to zero angle of attack, the effects of in-plane forebody pitch and yaw (cross) flow over the dome had to be quantified and factored into the dome cooling system design. The separated, viscous flow in front of the dome is not readily scalable at high angle-of-attack conditions, so additional full-scale wind tunnel testing was required. APL used computational fluid dynamics (CFD) analysis as a design tool to help determine the desired position of yaw coolant slots prior to initiation of full-scale wind tunnel testing. The internal contours of the coolant slot were also specified as part of the CFD studies. The CFD results provided valuable insight into the flow-field structure and coolant over the dome surface as functions of the coolant slot design and the coolant flow rate. The CFD predictions subsequently were validated against wind tunnel and flight test data, where good agreement was observed.

Once the basic cooling gas slot configuration was determined, full-scale dome heating experiments were conducted using flight prototype hardware. The purpose of these tests was to identify the design drivers and ensure adequate dome cooling over the Block IVA engagement space. APL provided the Navy with recommendations and planning for these aerothermal data collection tests, which were conducted at the Arnold Engineering Development Center Aerodynamics and Propulsion Test Unit wind tunnel, the NASA Langley 8-Foot High Temperature wind tunnel, the Holloman High Speed Test Track rocket sled, and the Calspan–University at Buffalo Research Center (CUBRC) Large Energy National Shock tunnel, leg two (LENS II).

APL designed and fabricated the thin-walled calorimeter domes used to gather the aerothermal data from many of these wind tunnels. The metal domes incorporated a grid of thermocouples spot-welded to the back surface of the dome to measure temperature during the testing. The calorimeters underwent extensive developmental testing in the APL Cell 4 wind tunnel to ensure reliable operation. APL-developed calorimeter domes were also flown on the Block IVA CTV missions. The structural integrity and the expected thermocouple response of the CTV calorimeter dome flight hardware were demonstrated via testing in the APL Cell 4 wind tunnel prior to the CTV-1 mission. Figure 9 shows the dome calorimeter during the peak-temperature portion of the pre-CTV-1 wind tunnel demonstration test. The dome calorimeter showed no signs of structural degradation, and the dome thermocouples operated as expected during the test.

The APL calorimeter design was subsequently successfully used to collect aerothermal dome data from both Block IVA CTV flight tests. Raytheon and APL

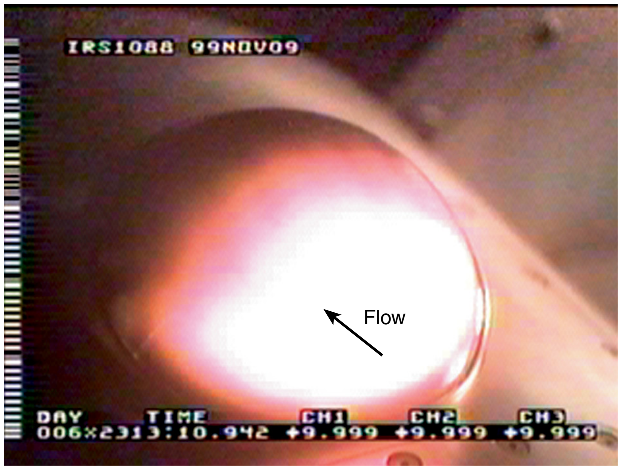

Figure 9. Video image of a metal calorimeter dome during testing in the APL Cell 4 wind tunnel. The testing was performed to demonstrate that the uncooled dome would survive and would allow dome temperatures to be recorded during the Block IVA CTV flight tests.

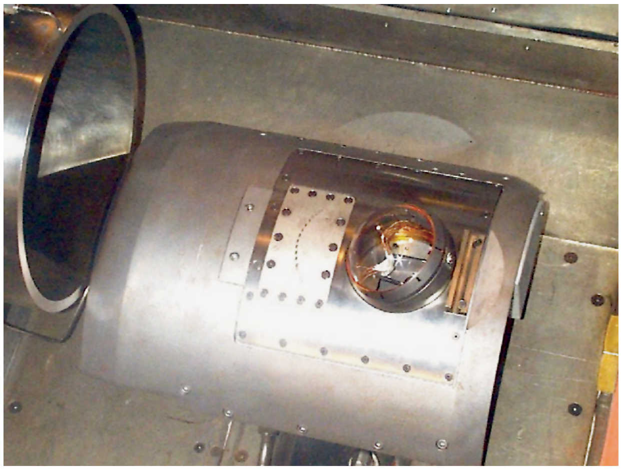

Figure 10. Setup for testing of a sapphire IR dome in the APL Cell 4 wind tunnel. The flow during the test is provided from the tunnel exit nozzle, which is the round opening on the left.

analyzed the flight and wind tunnel aerothermal data to develop engineering correlations for the dome heating. These engineering correlations were used by Raytheon with thermostructural models of the sapphire dome to assess how the sapphire dome would respond to the flight environment and, therefore, how to best meter the dome coolant gas during tactical flights. Periodically throughout this process, APL tested actual sapphire dome assemblies in the Cell 4 wind tunnel to demonstrate directly the survival characteristics of the sapphire dome, thus validating the aerothermal analysis. Figure 10 shows the test setup for these sapphire dome tests.

In addition to the dome survival issues, APL also quantified dome aero-optical effects. There are several mechanisms by which target images are distorted by the flow field in front of the dome: the target location is shifted (refracted) by mean density gradients (e.g., shock waves), the target image is blurred (i.e., reduced in intensity and resolution) when passing through the density gradients, and the turbulent flow over the dome blurs the target image and generates target jitter (high-frequency image motion). Flow-field–induced aero-optical effects were measured at CUBRC using the Aero-Optics Evaluation Center in LENS I. For these tests, the Navy used a highly sensitive instrumentation suite that allowed boresight shift and blur to be measured on a full-scale Block IVA missile forebody and dome at high- and mid-altitude flight conditions. The results were analyzed by APL and forwarded to Raytheon. A complementary modeling effort (being performed under subcontract for APL) is also under way to produce engineering models of boresight error and blur for incorporation into the Block IVA 6-DOF simulation.

Optical distortion can also occur from asymmetrical heating of the dome itself. This dome heating not only causes the dome to become nonhemispherical but also results in nonuniform index of refraction properties throughout the dome structure. APL modeling and testing to address this aerothermal-induced optical distortion is discussed in the article by Duncan et al., this issue. In general, the heated dome effects have much greater impact on aero-optical characteristics than the flow-field effects for typical missile flight conditions.

SUMMARY

APL is conducting high-fidelity simulation and analysis of the Block IVA missile hardware and software design to provide confidence that the functional design will meet TBMD requirements. This functional analysis is supplemented by testing of actual implemented guidance section hardware and integrated software in the APL GSEL. Similarly, APL performed wind tunnel testing and analysis to establish the underlying phenomenology upon which the Block IVA IR dome cooling system design was based and to verify IR dome survival in the stressing aerothermal flight environment. This synergistic and iterative use of analysis, simulation, and testing is key to the systems engineering approach that has been applied by APL since the early days of the Standard Missile Program. Continued application of this approach in support of future guided flight tests will ensure that the Block IVA weapon system design meets its TBMD requirements.

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