Overview of the Fire Control Loop Process for Aegis LEAP Intercept

Mark A. Landis

This article provides an overview of the fire control loop process for the Navy Theater Wide Aegis Lightweight Exo-atmospheric Projectile (LEAP) Intercept (ALI) project. The goal of the project is to launch a Standard Missile-3 (SM-3) from an Aegis cruiser to intercept a Theater Ballistic Missile target in exo-atmospheric flight. The article describes the fire control process as a series of five distinct loops throughout the ALI mission: prelaunch, boost, endo-midcourse, exo-midcourse, and terminal. A discussion is provided for each fire control loop, including the available sensor data that are provided as input into the loop, the process to ensure closure of the loop, and the interaction between the SM-3 and Aegis Weapon System.

INTRODUCTION

The Navy Theater Wide Program was established to give the U.S. Navy a much needed, rapidly deployable, highly mobile, defense-in-depth Theater Ballistic Missile Defense (TBMD) capability. The initial phase includes the Aegis Lightweight Exo-atmospheric Projectile (LEAP) Intercept (ALI) project and related risk reduction activities. The goal of the ALI project is to launch a Standard Missile-3 (SM-3) from an Aegis cruiser located off the Pacific Missile Range Facility to intercept a ballistic missile target in exo-atmospheric flight.

The SM-3 is a new four-stage variant of Standard Missile designed for an exo-atmospheric intercept of ballistic missiles. The SM-3 uses the first two stages of the SM-2 Block IV missile. The third and fourth stages apply technologies developed under the LEAP Program funded by the Strategic Defense Initiative Office and later the Ballistic Missile Defense Organization. The third stage uses a dual-pulse solid propellant rocket motor to increase the missile velocity prior to ejecting the fourth stage, or kinetic warhead (KW). The KW uses a longwave infrared (IR) seeker and the Solid-propellant Divert and Attitude Control System (SDACS) to guide to a hit-to-kill intercept of the ballistic target.

BACKGROUND

The Aegis Weapon System (AWS) was originally designed for an anti-air warfare (AAW) mission. For this mission, the AWS followed the “detect, control, and engage” paradigm. The detect, control, and engage process is performed by the AN/SPY-1 radar, command and decision (C&D) function, Weapons Control System (WCS), and Standard Missile. The SPY-1 radar searches, detects, and tracks potential targets, C&D assesses and evaluates potential targets, and the WCS and missile are used to engage and intercept the target.

To understand the fire control loop, one must define "fire control": the set of functions and processes performed by a combatant, firing guided missiles, to effect intercept of a designated target. The functions that make up the fire control loop span portions of detect and control as well as all of engage (Fig. 1).

To describe the ALI concept in terms of successful closure of the fire control loop, the differences between an AAW mission and the ALI mission must be understood.

- With the TBM threat, the SPY-1 radar must search and detect targets much farther away than is typical for an AAW mission.
- The guided missile being used to engage these targets flies twice as fast and five times as high as any other Standard Missile.
- The missile will be flying in the exo-atmosphere, where maneuver capability is only available during fixed intervals of time, unlike endo-atmospheric AAW engagements with continuous aerodynamic maneuver capability.
- The KW IR sensor does not acquire the target until committing to the terminal phase of flight.
- During the terminal phase, the KW must hit the TBM target for mission success rather than relying on a detonating warhead to kill an AAW threat.

All of these factors prompted a review of the fire control loop for ALI.

To explain the fire control loop process, the notion of a feedback control system is used (Fig. 2). Here, the control process acts to minimize the error signal. In simplistic terms, for the fire control loop, the input signal is the measured target position vector, and the feedback signal is the measured missile position vector. The resultant error signal is the relative target-to-missile position vector. The objective of the ALI fire control loop is to drive the error signal to zero (i.e., hit the target). The fire control process can use multiple sensors, involve more than one feedback loop, and be distributed between the ship and guided missile. Through the rest of the article, the fire control loop will be described in this context.

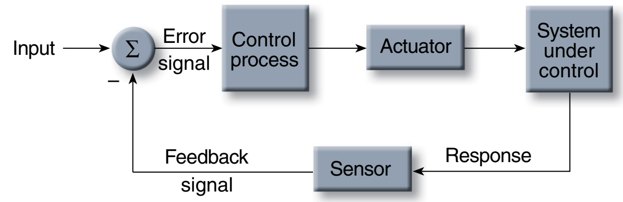

Figure 2. Basic feedback control system diagram.

ALI FIRE CONTROL LOOP

The ALI fire control loop can be broken down into five individual loops that follow a typical ALI engagement timeline (Fig. 3). The scenario starts with the launch of the single-stage, unitary test target vehicle (TTV) from the Pacific Missile Range Facility. The TTV M56A1 rocket motor burns for 63 s, followed by ballistic flight; target attitude is controlled by the Cold Gas Attitude Control System onboard the TTV. The SPY-1 radar will place search sectors near the TTV launch point and will detect the TTV shortly after it

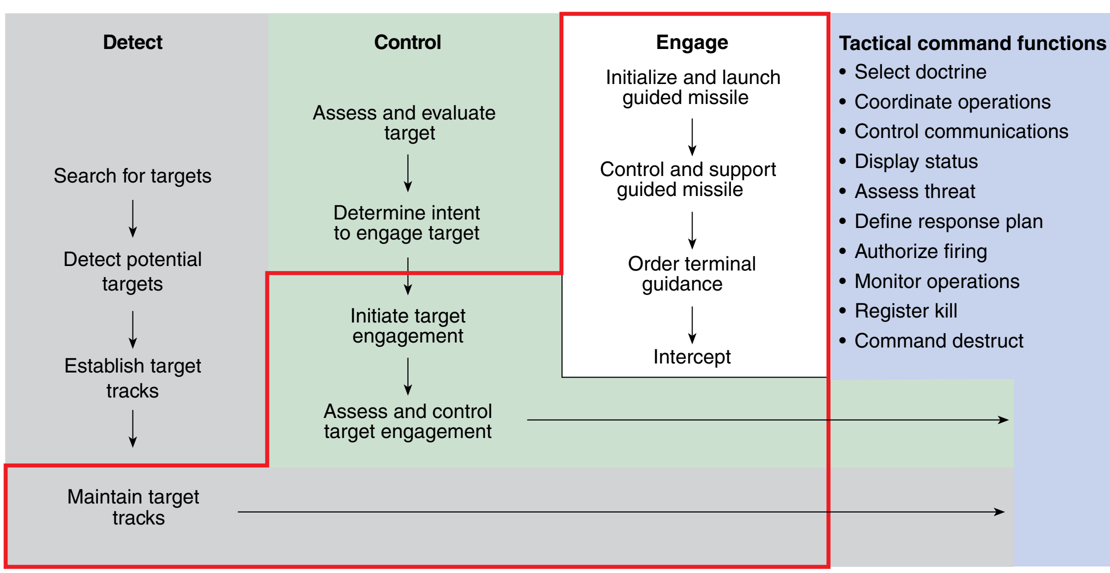

Figure 1. Engagement process functions (functions within the fire control loop are contained within the red border).

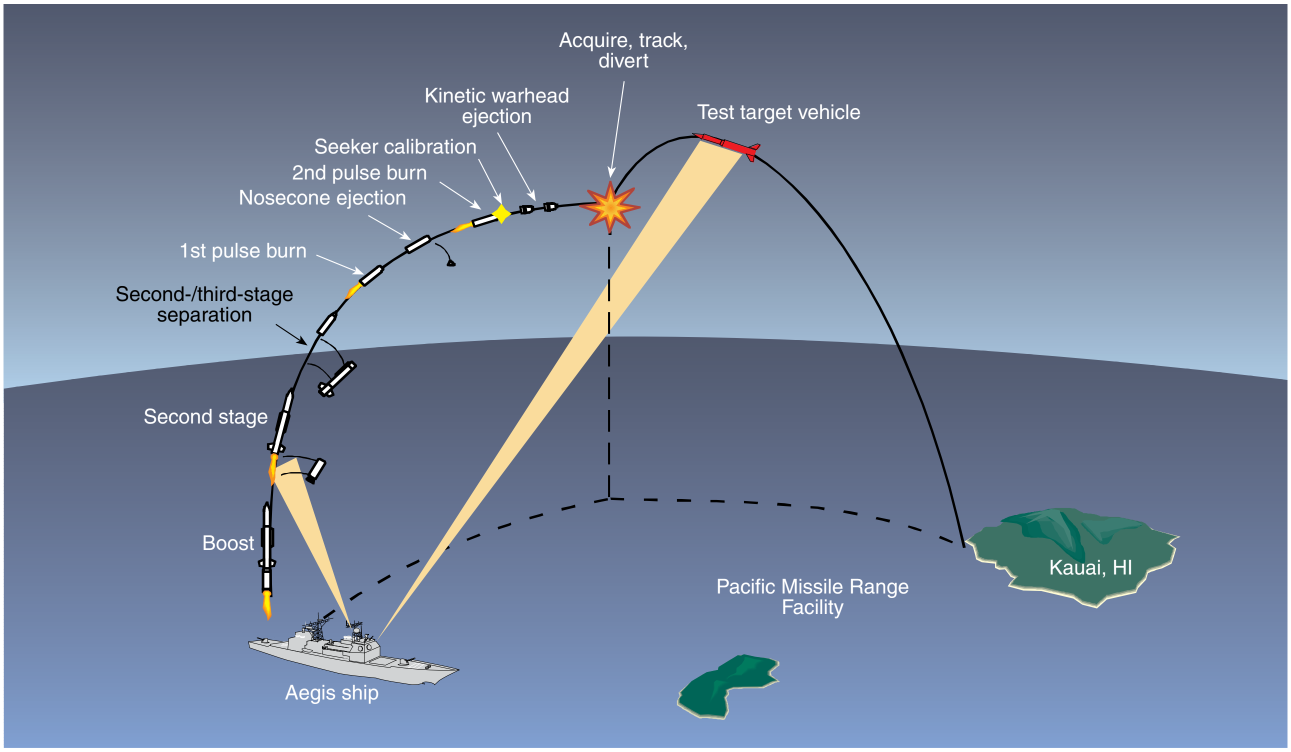

Figure 3. ALI engagement scenario.

breaks the radar horizon. After the TTV is in track and the TTV rocket motor has burned out, C&D will make a determination of engageability. For ALI, this is done simply by ballistic propagation of the TTV to splash. If this splash point is within a predetermined area, C&D will issue an engagement order to the WCS.

At this point, the ALI fire control process starts. Each individual loop within the fire control loop—prelaunch, boost, endo-midcourse, exo-midcourse, and terminal—is described in detail in following sections.

Prelaunch

The fire control process begins with the prelaunch loop (Fig. 4), which is initiated when the engagement order from C&D is given to the Aegis WCS. At this point in the timeline, the WCS is taking raw radar measurements of the target from the SPY-1 radar and running them through a ballistic track filter to estimate target position (R_t) and velocity. To perform this filtering, the WCS takes ship position, velocity, and attitude data from the shipboard navigation system (WSN-7).

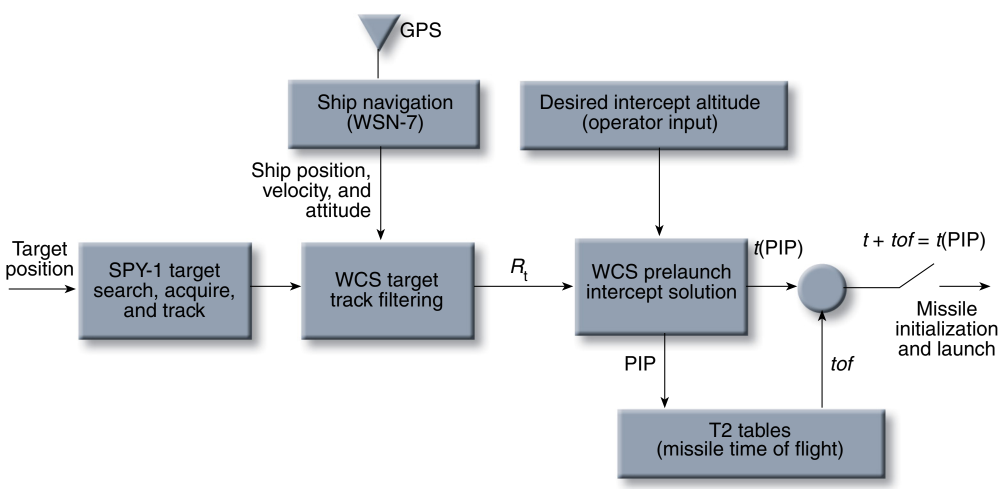

Figure 4. The ALI prelaunch fire control loop. The engagement order for an ALI mission is typically sent to the WCS 79 s after target launch. The SM-3 missile launch event takes place approximately 359 s after target launch.

These data are used to stabilize the radar data and to account for apparent target acceleration due to ship motion. Once an estimate of the target is generated from the filtering process it is used in the WCS prelaunch intercept solution. That solution propagates the target position to a desired intercept altitude, which is input to the system via operator action. The solution also calculates the time (t) for the target to reach the desired altitude. This time is compared to a missile time of flight (tof) value, which is derived from tables stored in the WCS referred to as T2 tables. The T2 table provides a table look-up value of missile flight time given a downrange and altitude of the predicted intercept point (PIP). The WCS then compares the current time plus the missile time of flight with the time for the target to get to the PIP. When these values are equal, the WCS will initialize the missile and inform an operator to launch it. For ALI, the intercept attempt will be on the descent side of the TTV trajectory. This results in about 280 s of time in the prelaunch loop.

Missile initialization is key to the fire control loop since this step sets a common time frame and coordinate frame for communication of data between the ship system and missile during flight. As with previous Standard Missiles, SM-3 is initialized (Fig. 5) by the WCS via the Vertical Launching System (VLS). New for SM-3 is the initialization of a GPS receiver onboard the missile as well as the ability of the missile to be powered externally by ship-supplied power via the VLS.

The GPS initialization (or hot-start) data message provides the GPS receiver with a very accurate time mark strobe, time mark data, and satellite ephemeris information. The shipboard system providing these data is the VLS GPS integrator (VGI), which uses the same type of GPS receiver employed by the missile to provide the hot-start data over a fiber-optic interface. The fiber-optic connection is required to get the highly accurate timing information needed to assure rapid missile GPS acquisition after launch. The external power is needed for prelaunch GPS initialization and is used for a missile health and status check prior to missile operation. Once the missile is properly initialized and passes its built-in test, it relays a missile-ready signal to the VLS that closes the firing interlock and ignites the Mk 72 booster rocket motor.

Boost Phase

The engagement sequence then transitions to the boost phase fire control loop (Fig. 6), which has heritage to the SM-2 Block IV missile. Here the input to the fire control loop is not directly the target position; rather, it is the desired velocity vector at the end of boost based on target data from the SPY-1 radar and the prelaunch intercept PIP. The initialization message specifies a desired vertical velocity vector direction (VLEG) and a horizontal velocity vector direction (bearing). During the boost phase, the missile uses its onboard inertial navigator—Inertial Reference and Measurement Unit (IRU/IMU)—to provide missile position, velocity, and attitude. These data, along with the initialization, are provided to pitch-over guidance. The pitch-over guidance algorithm uses the IRU feedback to calculate the current velocity vector direction and derives a flight path angle command (E_g, B_g) to force that vector to the VLEG and bearing per the initialization message at booster separation. Also note in Fig. 6 an inner control loop that uses missile body rate feedback to the autopilot to maintain airframe stability.

To enable a smooth transition to the next fire control loop, communication between the ship and missile must be established. This is being performed during the boost phase. Shortly after launch, the SPY-1 radar places search beams at the expected missile position. The radar will then send an acquisition beam and message. If the missile receives the uplink, the missile beacon transponder will reply with a downlink. Once this link is established, the WCS will use the raw missile beacon track data from SPY-1 as input into a missile filter

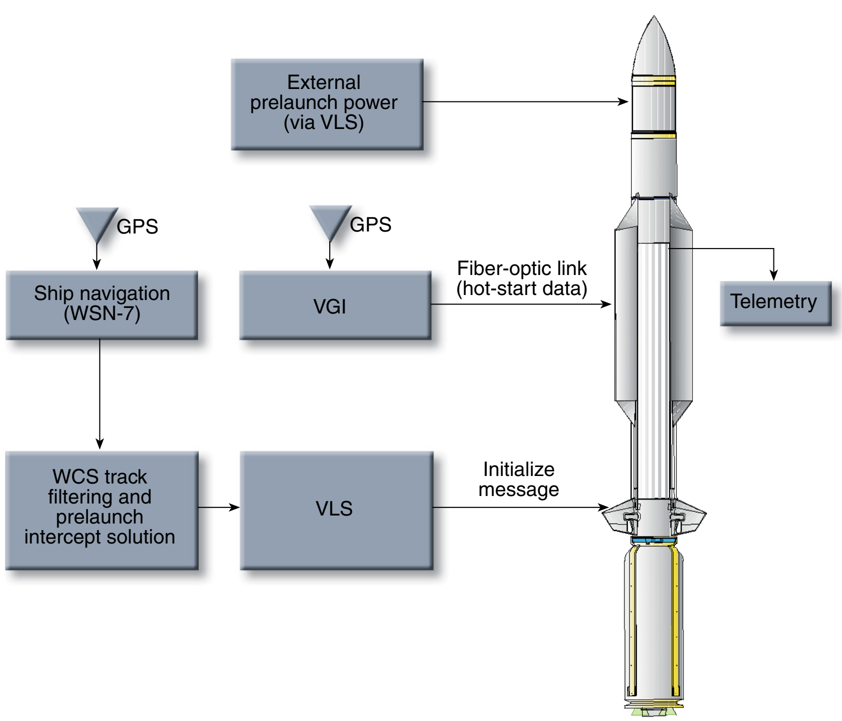

Figure 5. Standard Missile-3 initialization diagram.

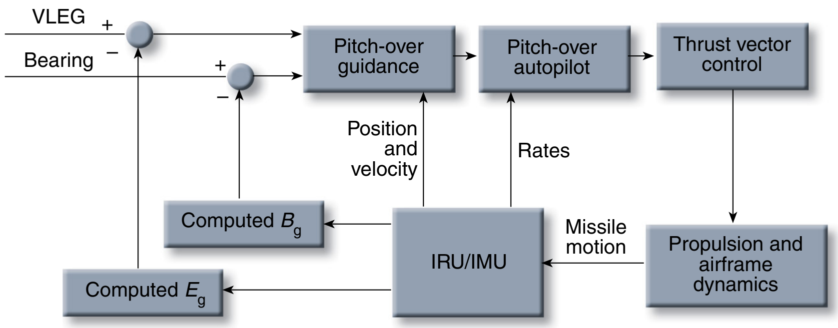

Figure 6. The ALI boost phase fire control loop. The initialization data provided as input to the loop are based on the PIP from prelaunch. The vertical and horizontal velocity vector commands (VLEG, bearing) are calculated so that the achieved missile position and heading at the end of boost will be on an intercept trajectory. The boost phase fire control loop, from missile launch to booster separation, lasts approximately 6.5 s.

to estimate missile position and velocity. These data will be required for the next fire control loop.

Endo-Midcourse Phase

The endo-midcourse phase (Fig. 7) uses AWS command guidance to close the fire control loop. This phase is similar to the one used in previous Standard Missile variants in the AWS. The AWS has estimates of both the target and missile tracks (R_t and R_m, respectively) based on the SPY-1 track and WCS filtering. These data are used in WCS midcourse guidance to calculate acceleration commands that are sent to the missile via the uplink.

For second-stage guidance, the WCS propagates the target to the PIP using the filtered target position and velocity. The WCS also estimates the remaining velocity to be gained by the missile using inputs of filtered missile position and velocity as well as an understanding of the event sequence being performed by the missile. In other words, the WCS must predict when the two pulses of the third-stage rocket motor will burn. For ALI, these events are based on a combination of time and altitude. The objective of midcourse guidance is to reduce the heading error as much as possible prior to the missile entering the exo-midcourse phase.

The transition from endo-midcourse to exo-midcourse is complicated, and many separate events are taking place during endo-midcourse to prepare for it. For both the boost and endo-midcourse phases of flight, the missile is using heritage Block IV inertial navigation to provide missile position, velocity, and attitude data. This navigator is not accurate enough for exo-midcourse flight, however. As stated in the prelaunch discussion, the missile is equipped with the GPS. The GPS-Aided Inertial Navigation System (GAINS) blends IMU, GPS, and radar data to provide a highly accurate navigation solution. During endo-midcourse, the GPS receiver attempts to acquire the GPS satellites using the hot-start initialization data. Nominally, the missile will acquire the GPS during endo-midcourse and the GAINS solution will have time to converge prior to transitioning to exo-midcourse.

Another concern with the transition is the change in control of the missile from aerodynamic to exo-atmospheric. In preparation for this transition, the WCS midcourse guidance is designed to reduce the heading error while the missile is still in

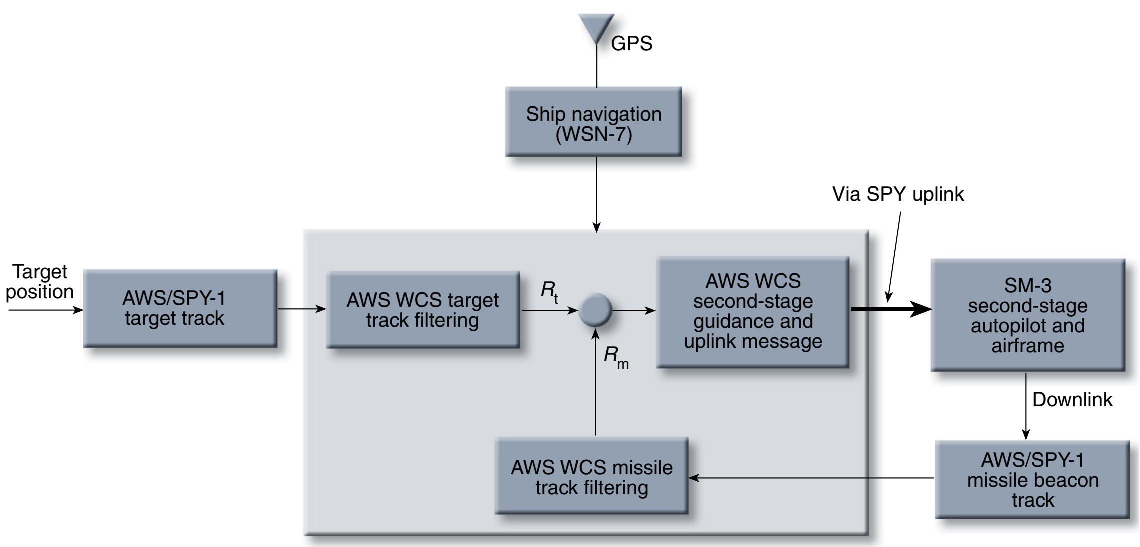

Figure 7. The ALI endo-midcourse phase fire control loop. This phase starts at booster separation and continues until the missile performs second- and third-stage separation, which for ALI occurs at approximately 54 s into SM-3 flight.

the atmosphere and can still perform reasonable maneuvers. At the same time, the missile autopilot is beginning to ramp down acceleration commands to maintain airframe stability prior to second- and third-stage separation. The second-stage autopilot is required to provide reduced body angles and rates at separation so that the third-stage control system, which is designed for exo-atmospheric control and therefore has smaller control authority, can capture and maintain stability.

Also, the information on the uplink must be changed to support the transition to exo-midcourse. The uplink is divided into two phases, the first containing acceleration commands for endo-midcourse guidance and the second containing target position and velocity for exo-midcourse. The uplink is transitioned during flight based on missile altitude.

Exo-Midcourse Phase

The exo-midcourse fire control loop (Fig. 8) is new for the AWS. The phase begins with the ignition of the first pulse (of two) of the third-stage rocket motor (TSRM) following separation of the third stage from the second stage. The third stage can actively guide the missile toward intercept only during a TSRM pulse burn. As opposed to endo-midcourse, third-stage guidance is performed onboard the missile. Estimates of target and missile tracks from the WCS are supplied to the missile via the uplink. These data, along with the GAINS estimates of missile position, velocity, and attitude, are fed to the third-stage guidance algorithm. The guidance commands are then provided to the third-stage autopilot, which uses body rate and angular feedback to stabilize the missile.

Third-stage guidance is referred to as "burnout reference guidance." As the name implies, guidance attempts to place the third stage on a collision course at the end of the last TSRM motor burn. For ALI, the scenario calls for *both* TSRM pulses to be used. Guidance extrapolates both target and missile state information to the time of motor burnout. At that point, guidance compares the missile velocity vector perpendicular to the line of sight (LOS) to the target velocity vector perpendicular to the LOS. If these vectors match, the missile is on a collision course with the target. If differences occur, guidance calculates a desired TSRM thrust vector to make the velocity vectors match. The guidance computations are done continuously during TSRM burns.

Between the TSRM burns, a mission sequence of events is exercised that provides the autopilot attitude control commands. Initially, the missile attempts to use the Attitude Control System (ACS) to hold a zero angle-of-attack profile, or align the centerline of the missile body to the velocity vector. In preparation for nosecone eject, the missile slowly moves the body away from the velocity vector, then holds the missile body attitude. The nosecone is ejected and the body attitude is returned to zero angle of attack in preparation for the second TSRM pulse burn. After the second TSRM pulse, the ACS is used to point toward the target LOS vector and provide other attitude maneuvers in preparation for KW ejection.

The transition from exo-midcourse to the terminal phase is critical. At a given time-to-go (t_{go}) to intercept, the third stage will command the KW battery to be activated and will point the KW away from the

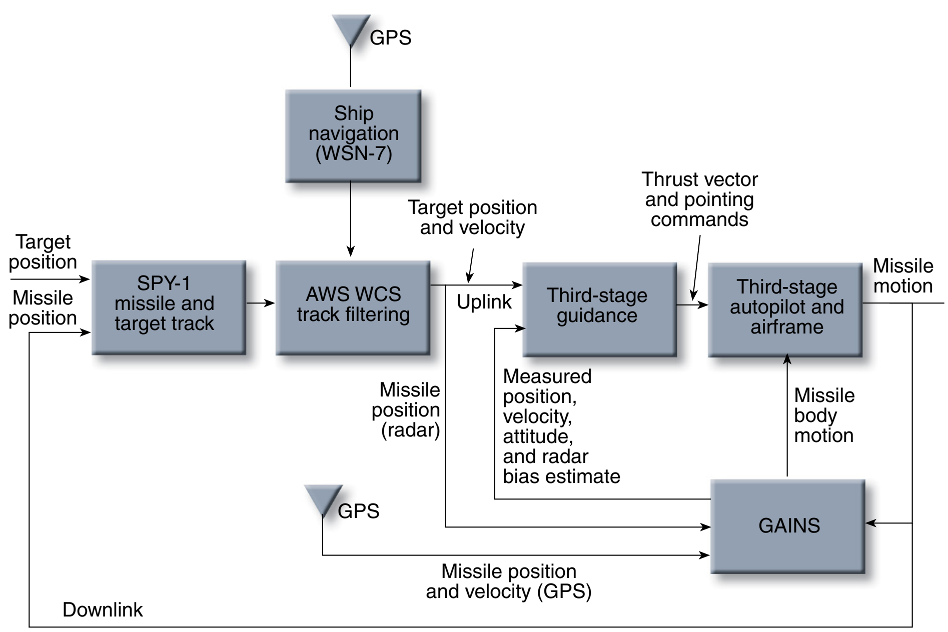

Figure 8. The ALI exo-midcourse phase fire control loop. This phase lasts from second- and third-stage separation to KW eject. For ALI, the time spent in exo-midcourse is approximately 64 s.

target LOS to a space background for seeker calibration. At the same time, the third stage will perform a roll maneuver to allow the KW to estimate the alignment of the third-stage navigator to the KW navigator. After completion of the calibration and transfer alignment, the third stage provides initialization data to the KW including target position and velocity and missile position, velocity, and attitude. The KW is then ejected at 24 s t_{go}.

Terminal Phase

Unlike traditional AAW engagements, the KW will be ejected and committed to terminal homing prior to terminal target acquisition. Therefore, the ALI system must ensure that the target will be within the field of regard (FOR) of the KW IR seeker and within the KW divert capability.

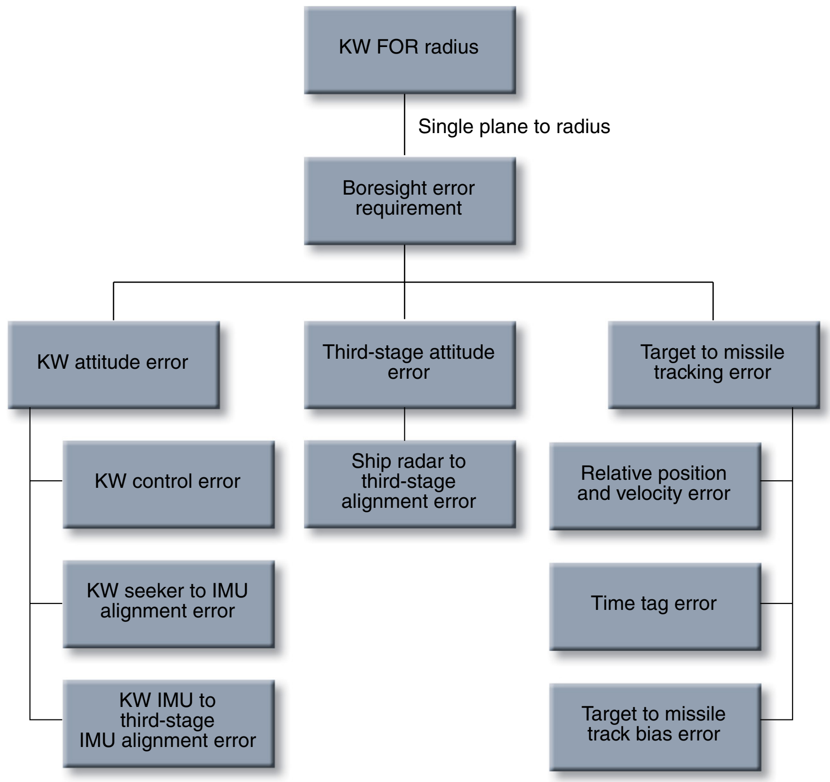

Figure 10. KW pointing error tree.

KW Pointing

A diagram of the KW pointing error, Fig. 9, shows that the target must be within the KW FOR in order for the KW to detect the target. The estimated target LOS vector is generated from the target and missile state information handed over to the KW from the third stage prior to eject. To ensure that the target will be within the FOR, an error tree (Fig. 10) was developed to account for all of the error sources contributing to the pointing error. The right branch of the tree contains the error in the targeting data due to the AWS. The contributors include relative target-to-missile position and velocity errors, time tag errors, and track-to-track bias error. The middle branch refers to the ability of the third-stage navigation system to align the missile navigation frame with the SPY-1 radar frame. This is critical for alignment of missile data and data provided by the shipboard system. The left branch shows the contributors due to alignment of the third stage and KW and the ability of the KW to point accurately. The KW FOR radius can be calculated based on the subsystem error budgets and is scenario dependent. For ALI, the subsystem error allocations were budgeted and the scenario was chosen to allow for a pointing error that is less than half of the KW IR seeker field of view (FOV), or 100% margin.

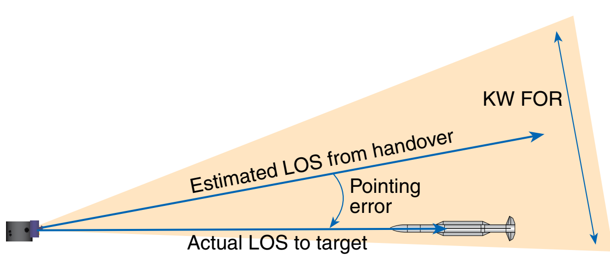

Figure 9. KW pointing error diagram.

The fire control loop from KW eject to target acquisition is shown in Fig. 11. Initially, the target state vector is provided by the third stage and is then propagated forward to the current time for pointing. The KW position, velocity, and attitude data are initialized from the third stage, and the KW uses its IMU and navigator to propagate its state vector information. After the SDACS is ignited and the KW stabilizes from the ejection transient, commands are generated from the navigator to point toward the estimated target LOS vector. The commands drive the ACS, which controls the ACS thrusters via thruster "on" time (t_{on}) to orient the KW body. This body motion is sensed by the IMU and is fed back to the navigator. At this point in the mission sequence, the IR seeker will be attempting to acquire the target, so no information from the seeker is used in this portion of the KW fire control loop. Also, because the target is not acquired, the KW is not actively guiding toward intercept. In Fig. 11, the green portions note the active part of the loop and the red indicate inactive portions.

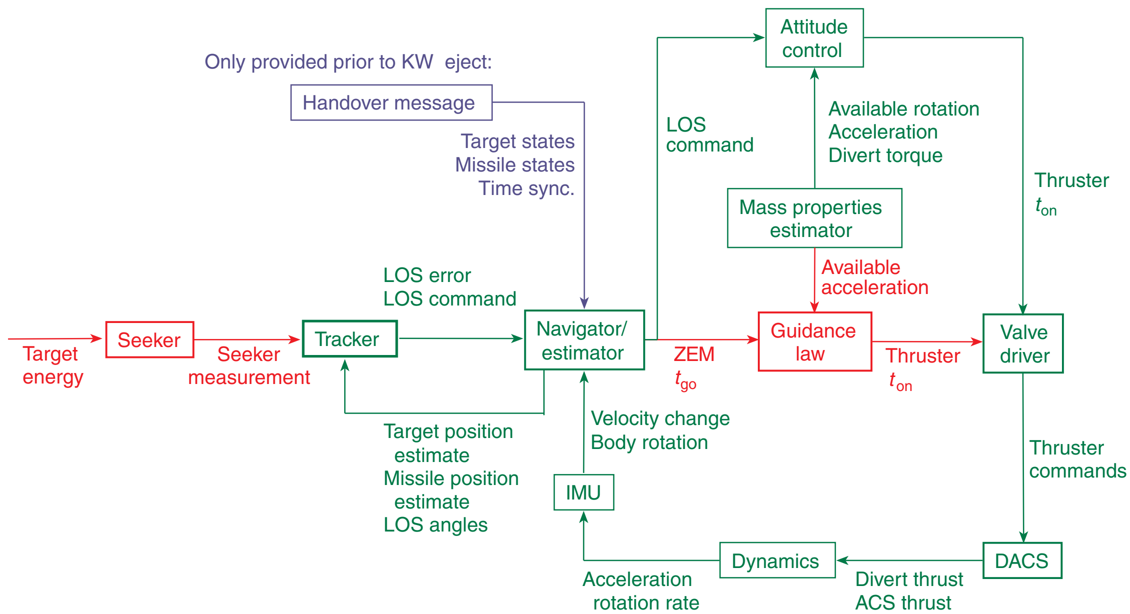

Figure 11. The ALI KW phase fire control loop (eject to acquisition). For ALI, this portion of the KW phase lasts for approximately 4 s.

KW Divert

At transition from exo-midcourse to terminal, the only remaining energy to reduce errors is in the KW divert and attitude control system (DACS). Because of the limited volume of the KW, divert capability is also limited. Therefore, the third stage must ensure that the zero-effort miss (ZEM; Fig. 12) distance at handover is less than the KW divert capability. As the name suggests, ZEM is simply the measured miss distance when the current missile and target positions and velocities (V_{kw} and V_t, respectively) are propagated to the closest point of approach. As with KW pointing, an error tree has been developed that shows the contributors to the third-stage ZEM (Fig. 13). The right side of the error tree is identical to that of the pointing error tree (Fig. 10). However, the errors are represented as propagated position errors rather than angular errors. These errors are propagated from the end of pulse 2 of the TSRM. This is the last opportunity for the third stage to affect the ZEM. The left side of the tree is the contribution from third-stage guidance, navigation, and control. As with the pointing error, navigation errors represent the ability of the third stage to align with the radar, except that the error is represented as a velocity error. The guidance algorithm error is due to uncertainty in TSRM performance, filtering, gravity model uncertainty, and guidance termination scheme. The control accuracy error is due to thrust vector control biases and dead-zone, alignment, and gain uncertainties. Again, the divert error tree (Fig. 13) is dependent on the budgeted subsystem errors and the scenario. As with the KW pointing error tree, the budgeted errors and scenario were chosen to allow for a third-stage ZEM that is half of the KW divert capability, or 100% margin.

After the KW IR seeker has acquired the target, the KW uses the seeker measurement information to estimate target position and actively guides to intercept. Figure 14 shows the KW fire control loop from acquisition to intercept. The KW estimates of position, velocity, and attitude are computed onboard the KW using information from the KW IMU. This information, along with the seeker measurements, is used to

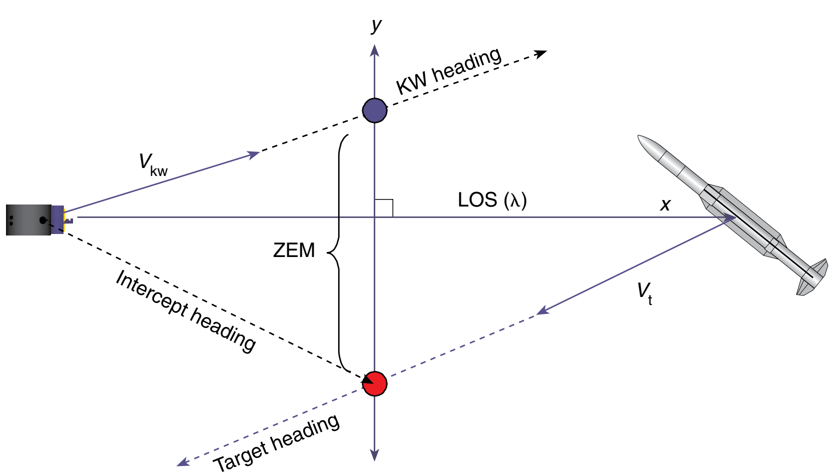

Figure 12. KW zero-effort miss (ZEM) distance diagram.

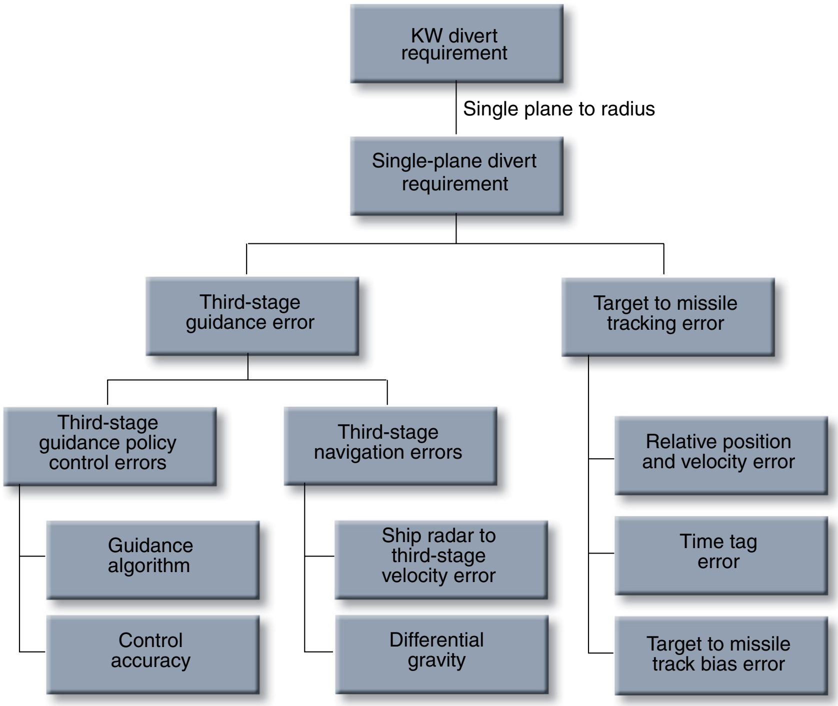

Figure 13. KW divert error tree.

calculate an estimate of ZEM for guidance and the pointing command for the ACS to keep the target in the track gate. Note that for the first four phases of the fire control loop, the target information was provided in three dimensions from the SPY-1 radar. For the terminal phase, the KW has two-dimensional measurements of angle only. The range or time-to-go information is calculated by propagating the data from the handover message. At this point, the KW calculates duty cycles for the attitude thrusters, and guidance calculates duty cycles for the divert thrusters. Because the SDACS supplies gas to both divert and attitude control thrusters, the KW must estimate the amount of energy available from the SDACS and coordinate the firing of the divert and attitude thrusters. Because the IR seeker is fixed to the body, the KW must remain pointed toward the target while diverting.

Once the KW has successfully ejected, acquired the target, and begun diverting, the last challenge is for the KW to actually hit the target. Again, hitting the target is different from a typical AAW engagement with Standard Missile where the missile tries to get within a certain miss distance and uses its fragmenting warhead to kill the target. In SM-3, the KW must manage the available divert energy and have small measurement errors in order to hit the target. Because the KW is in the exo-atmosphere and acts like a spacecraft, the management of the rocket motor is critical. Figure 15 shows the typical acceleration profile of the KW. The blue region represents a low thrust pulse that burns the entire time of KW operation for use initially with pointing and then to maintain attitude and correct for small divert errors. The red region

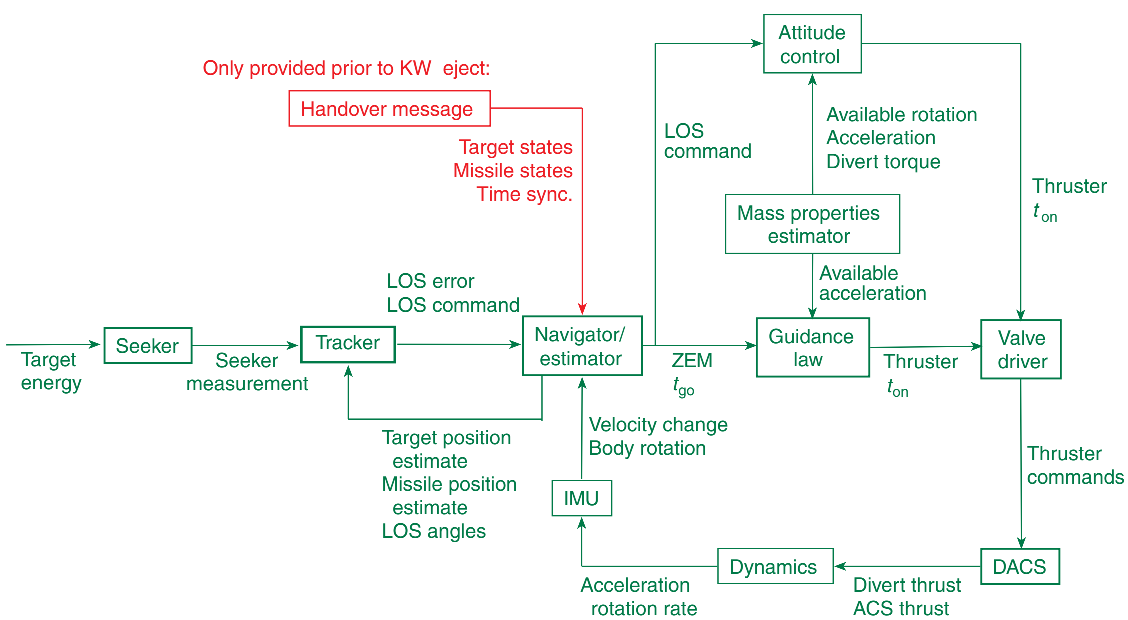

Figure 14. The ALI KW phase fire control loop (acquisition to intercept). For ALI, this portion of the KW phase is approximately 20 s.

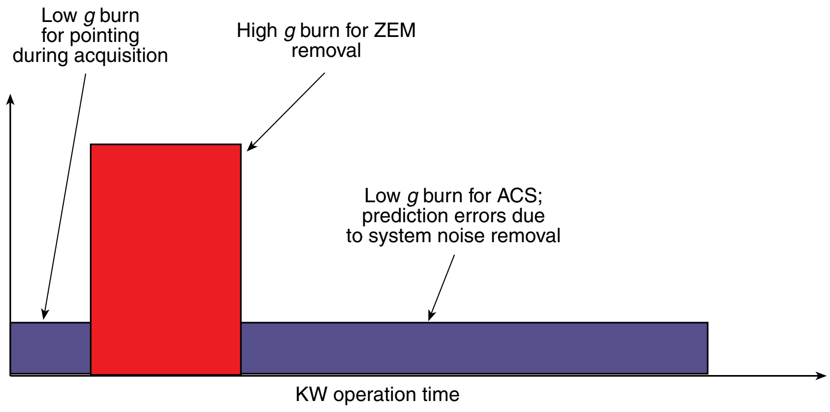

Figure 15. KW divert acceleration profile.

represents a high thrust pulse that is used after acquisition to reduce the handover ZEM. It is during this time that guidance attempts to null all of the ZEM inherited from the third stage.

Several factors allow the KW to hit the target. First, the intercept takes place in the exo-atmosphere against a ballistic target. The target does not perform lateral movements like weaving or diving; therefore, the only acceleration from the target is due to gravity. Second, the response time of the KW control system is substantially smaller than an aerodynamically controlled missile. The divert thruster commands are acted upon almost immediately in a space environment. An aerodynamic missile must actuate the command and allow the airframe dynamics time to respond in an aerodynamically uncertain environment. Finally, the KW has very small sensor noise sources. The two main noise sources are from the IR seeker and the IMU. The IR seeker is extremely accurate and, because it is used in space, no additional errors from seeker covers or windows are added. Also, the IMU uses a highly accurate fiber-optic gyro that provides high-rate inertial measurements. All of these factors provide confidence that the KW will hit the TBM target.

SUMMARY

The ALI system combines the AWS and SM-3 to demonstrate the ability to intercept a TBM target outside the atmosphere. The fire control loop paradigm used for AAW can also be used to describe the ALI system. The ALI fire control process can be summarized as five separate loops, each unique in its implementation; however, the underlying theme for all five loops is the use of closed-loop feedback. An understanding of the fire control loop is critical and allows a complicated system to be decomposed into simpler subfunctions. Figure 16 summarizes each loop required for ALI. To date, substantial analysis, simulation, ground tests, and flight tests have been performed to validate the integrity of the fire control loop. As the ALI system

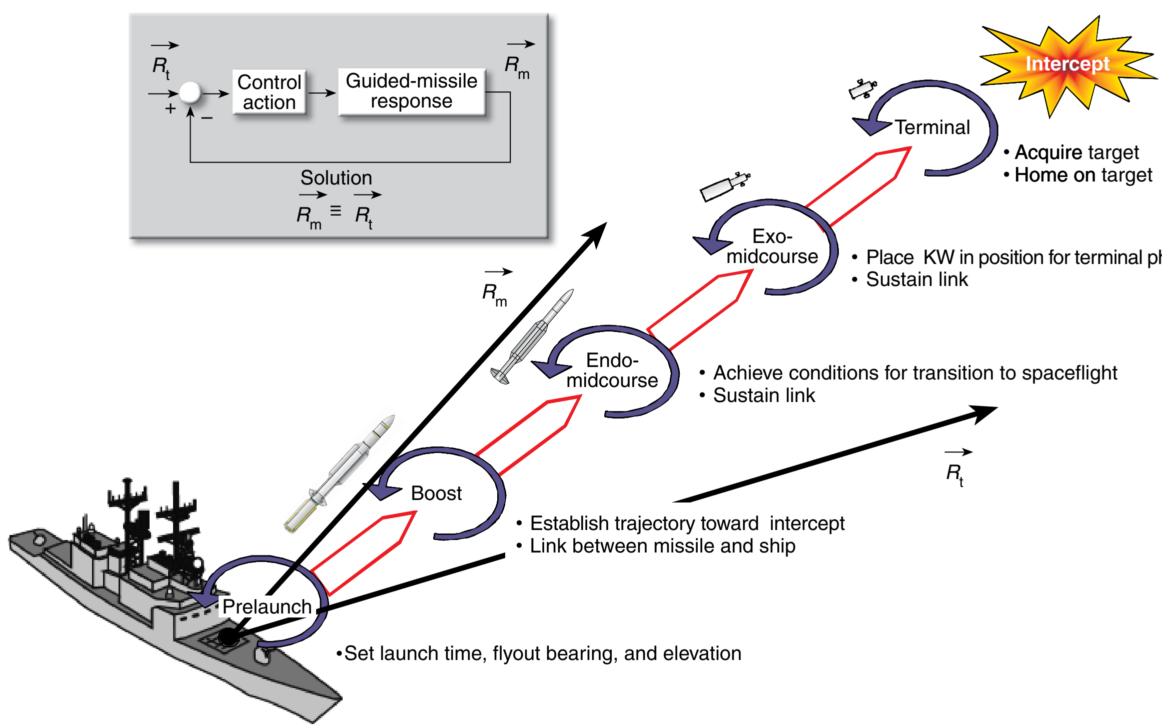

Figure 16. Summary of the ALI fire control loop.

completes the demonstration phase and transitions to a tactical weapon system, the fire control loop will be used as the basis to understand and apply new functionality to the system.

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THE AUTHOR

MARK A. LANDIS received his B.S. in electrical engineering from Drexel University in 1989 and an M.S. in electrical engineering from The Johns Hopkins University in 1993. Mr. Landis joined APL in 1989 and is the Chief Engineer for the SM-3 Aegis LEAP Intercept (ALI) Program as well as Supervisor of the Performance Assessment Section in ADSD's Theater Missile Systems Group. He is the chairman of the Performance, Prediction, and Assessment Working Group for the ALI Program and serves as the government representative on several SM-3 integrated product teams and working groups. He is coordinator for the SM-3 six-degree-of-freedom missile simulation and SM-3 simulation verification, validation, and accreditation. Mr. Landis has an extensive background in modeling, analysis, and simulation of missile systems as well as guidance, navigation, and controls systems. His e-mail address is mark.landis@jhuapl.edu.