Exo-atmospheric Intercepts: Bringing New Challenges to Standard Missile

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The Navy Theater Wide System is being designed to provide defense for U.S. forces and our Allies against medium- to long-range tactical ballistic missiles. As part of this system, a new variant of Standard Missile, SM-3, will be introduced to the Fleet. SM-3 will perform a hit-to-kill intercept of the ballistic missile while it is in exo-atmospheric flight (i.e., while outside the Earth's atmosphere). Exo-atmospheric flight and hit-to-kill intercepts have brought new challenges to the SM Program. These challenges have introduced new technologies, which in turn have created the need for new tests to be added to an already robust SM ground test program. This article discusses these new challenges and describes tests geared to verify SM-3 design, with emphasis given to those tests performed at APL.

INTRODUCTION

The threat of ballistic missile attacks to U.S. forces and our Allies continues to grow. Currently over 40 nations have the capability to launch ballistic missile attacks. Most of these missiles are not capable of reaching U.S. soil; nevertheless, they do pose a significant threat to our forces stationed overseas. Many of these nations also have the ability to build chemical, biological, or nuclear warheads, making the threat even more severe.

The Navy Theater Wide (NTW) System is being developed to defend against medium- to long-range tactical ballistic missiles launched against Allied and U.S. forces on foreign soil. The system leverages heavily on the Navy's large investment in the Aegis Weapons System (AWS) and Standard Missile (SM). The heart of the NTW System is the ability of the Aegis AN/SPY-1 radar to acquire and track ballistic missiles and the ability of the combat system to engage them by guiding the missile to an intercept. Modifications are being made to the AWS to change the logic consistent with tracking and engaging ballistic missiles rather than its traditional Anti-Air Warfare role.

In addition to modifications to the AWS, the NTW System is developing a new SM variant, SM-3. SM-3 is a four-stage missile deriving its heritage from the SM-2 Block IV used for Anti-Air Warfare as well as technologies developed under the Strategic Defense Initiative Organization and later the Ballistic Missile Defense Organization Lightweight Exo-atmospheric Projectile (LEAP) Program.

The SM Program has a legacy dating back to the mid-1940s with the advent of the Talos, Terrier, and Tartar programs. Throughout the more than 50 years of developing surface-to-air variants, a robust ground test program has been developed. Many of these tests were implemented as a result of problems experienced during flight tests and were added in an attempt to prevent future flight failures. Design verification tests (DVTs) are typically performed on an inert operational missile, which is identical to a flight round except that there is no live ordnance or rocket motors. DVTs are done to prove that the design will maintain functionality while exposed to various environments and conditions to which the flight round will be subjected. Many of the extensive ground tests for SM-3 are based on SM experiences; however, several tests have been added because of the new environment created by the missile.

This article discusses ground testing added to the typical SM ground test program, specifically for the SM-3 Program, with emphasis on tests performed at APL. It does not discuss the extensive ground testing that has been adopted from the SM-2 Block IV Program or the numerous safety tests that are required prior to launching a missile from a ship. An evaluation of the SM-3 ground test program is discussed by Rogers, this issue.

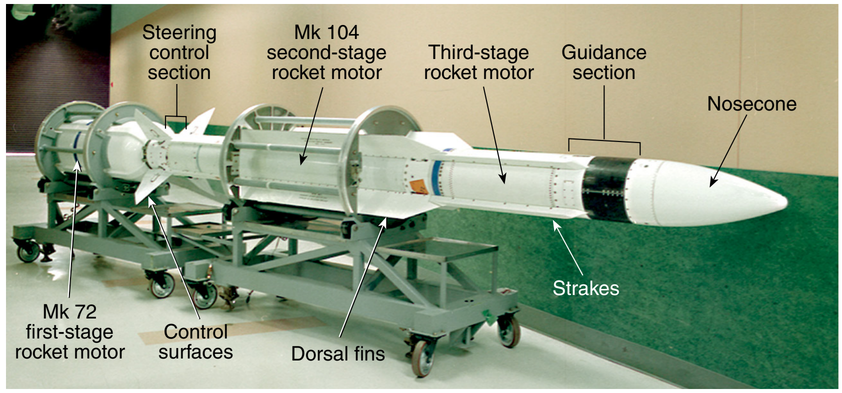

Figure 1. The SM-3 missile.

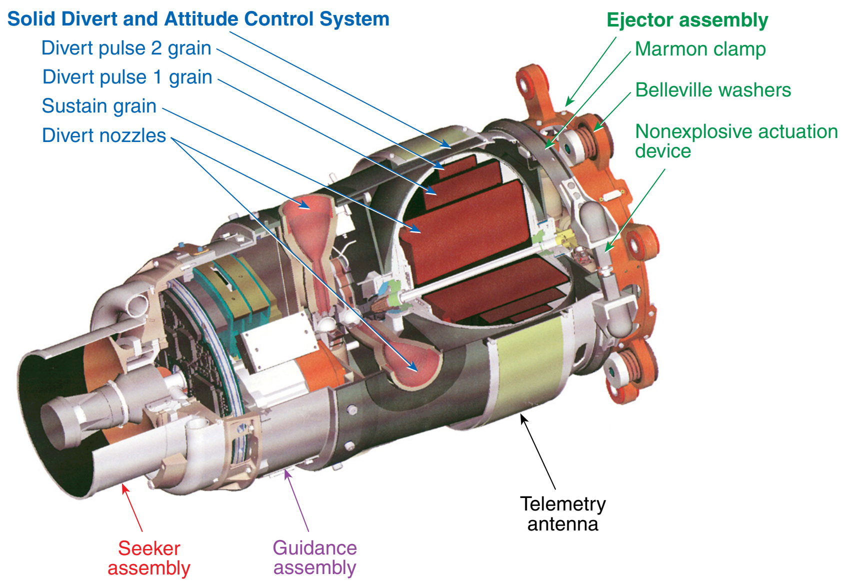

Figure 2. Kinetic warhead overview.

ALI DEMONSTRATION

The ability of SM-3, operating in conjunction with the AWS, is being demonstrated as part of the Aegis LEAP Intercept (ALI) Program. A target will be launched from the Kauai Test Facility, and the USS *Lake Erie* (CG 70), operating approximately 300 miles from the coast of Kauai, will acquire the target using the AN/SPY-1B(V) radar and launch the SM-3 to intercept it.

We focus here on the SM-3 missile (Fig. 1), specifically the ALI configuration. Components used from SM-2 Block IV include the first- and second-stage rocket motors (Mk 72 and Mk 104, respectively), second-stage steering control section, dorsal fins, and Aegis transceiver plate used for communication with the ship. Technologies used from the LEAP Program include the third-stage rocket motor (TSRM), GPS-Aided Inertial Navigation System (GAINS), and fourth-stage kinetic warhead (KW).

The SM-3 KW (Fig. 2) consists of a seeker assembly, guidance assembly, Solid-propellant Divert and Attitude Control System (SDACS), and ejector assembly. The seeker assembly comprises a long-wave infrared (IR) sensor with associated optics and a signal processor. The guidance assembly includes a guidance processor, valve driver, telemeter, and battery. The SDACS has a gas generator with three solid propellant grains—sustain, pulse 1 divert, and pulse 2 divert; these are detailed later in the section. Wrapped around the SDACS is the telemetry antenna. The ejector assembly uses a marmon-type clamp to hold the KW to the third-stage guidance section. Upon command, a nonexplosive actuation device allows the clamp to open. Once opened, belleville washers (essentially springs) at three locations force the KW from the third stage.

APL is the Round-level Technical Direction Agent for SM-3. Other responsible parties are as follows: Raytheon Missile Systems Company (RMSC, formerly Hughes Missile Systems Co.), as Design Agent, for round-level design and integration, integration of the KW, and design and fabrication of the IR seeker and signal processor; Boeing North American for the design of the KW guidance and ejector assemblies; and Alliant Techsystems Inc. (formerly Thiokol Elkton) for the TSRM and KW SDACS.

A typical engagement scenario for the ALI mission is shown in Fig. 3. Shortly after launch of the target, the Aegis cruiser detects the target using the AN/SPY-1 radar. Upon burnout of the target motor, the AWS calculates a ballistic trajectory and computes a predicted intercept point. Knowing the SM-3 kinematics, the AWS determines the best launch time for SM-3. After SM-3 is prepared for flight, the missile is launched from the Vertical Launching System (VLS) and is accelerated by the Mk 72 solid propellant rocket motor. During this "boost" phase, four thrust vector–controlled nozzles at the aft end of the Mk 72 provide the missile control. The missile pierces the canister cover during egress, flies vertically until it reaches a safe distance from the ship, and then maneuvers to fly to a predetermined point.

Upon burnout of the Mk 72 motor, separation of the first and second stages occurs, and the second-stage Mk 104 solid propellant rocket motor is ignited. During this "endo-midcourse" phase, the vehicle is further accelerated but remains within the Earth's atmosphere and hence uses aerodynamic control created by the tail fins. Acceleration commands, sent to the missile via Aegis uplinks, are received by the missile and are turned into tail commands by the autopilot. The ship, tracking the target and missile with the AN/SPY-1 radar, attempts to put the missile on a collision course with the target. After burnout of the Mk 104 motor, the missile coasts to an altitude of 56 km, at which time the third stage separates from the second stage. While coasting, an in-flight alignment is executed to ensure that the missile and ship coordinate frames are aligned. This is done because the missile will provide its own guidance and navigation solution after third-stage separation but will continue to receive target position and velocity from the ship.

After second-stage separation, the first of the TSRM's two pulses is ignited. This portion of flight is referred to as the "exo-midcourse" phase. During rocket motor operation, control is maintained by the TSRM thrust vector control. Immediately after pulse 1 burnout, the Warm Gas Attitude Control System (WGACS) is used to maintain proper vehicle orientation. The WGACS consists of four separate solid propellant gas generators that are fired separately and burn for approximately 3 s. Four exhaust nozzles in a cruciform orientation allow control in the pitch and yaw planes of the missile (Fig. 4). The Cold Gas Attitude Control System

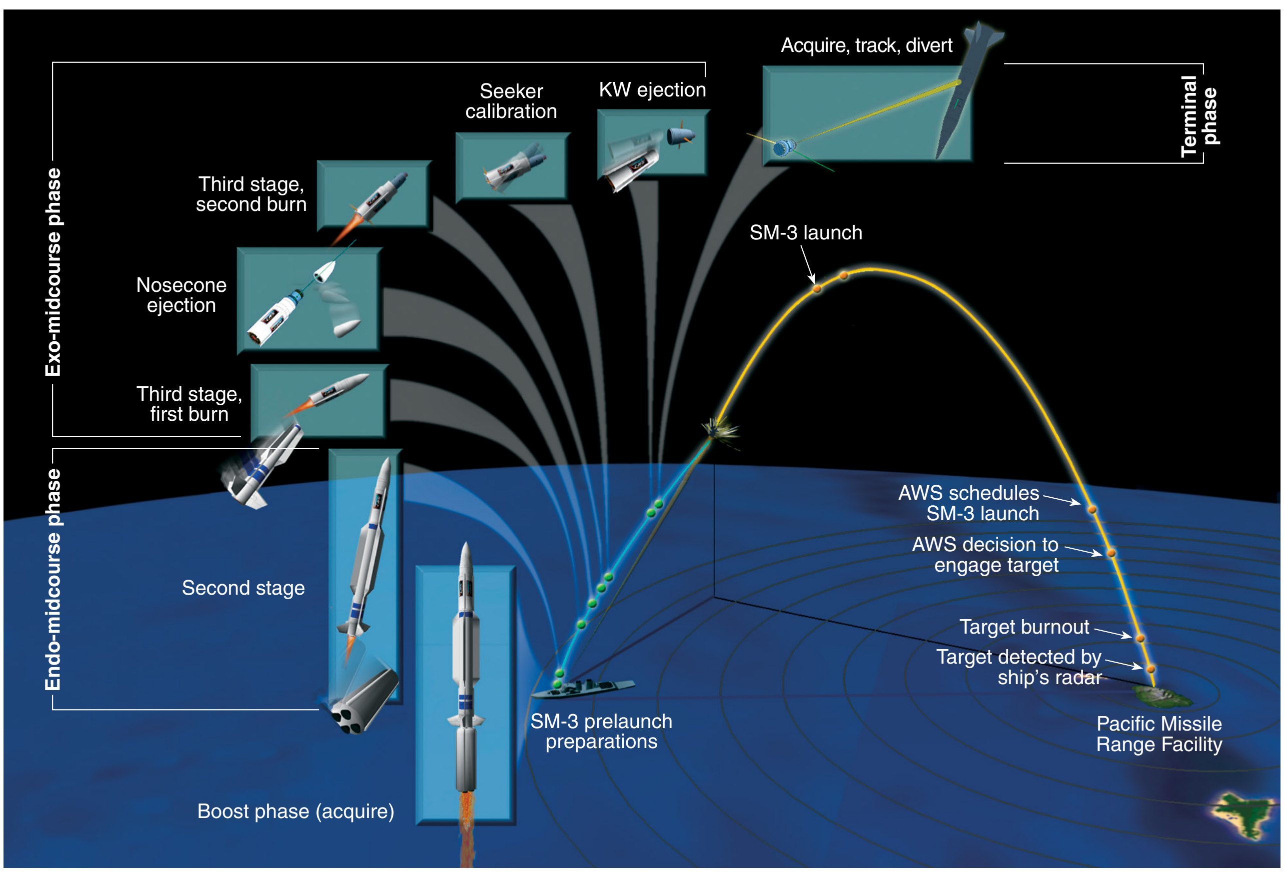

Figure 3. ALI engagement sequence.

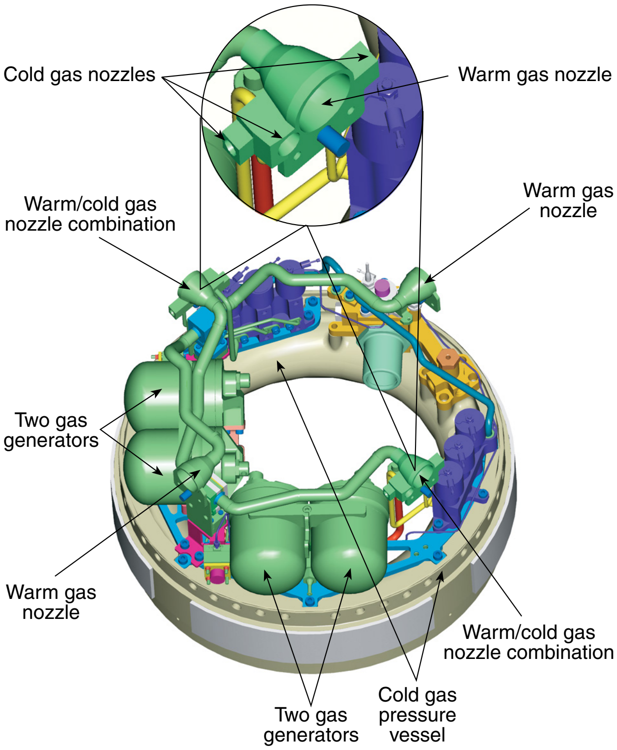

Figure 4. Hybrid Warm/Cold Gas Attitude Control System.

(CGACS) provides lower thrust levels using nitrogen stored at 10,000 psi. The nitrogen is exhausted through six nozzles to maintain pitch, yaw, and roll control at high altitudes. Two of the nozzle assemblies have a combination of warm and cold gas nozzles. Each assembly has a single nozzle for the warm gas and three orthogonal nozzles for the cold gas. Between the TSRM pulse 1 and pulse 2 burns, the CGACS is used to orient the vehicle at a 30° angle of attack to eject the nosecone. This is referred to as the pitch-to-ditch maneuver. The WGACS is then used to reorient the vehicle back to a path to the intercept point, and the second TSRM pulse is ignited.

After pulse 2 burnout, the CGACS is again used to orient the vehicle away from the target line of sight to perform a calibration of the KW's IR seeker while pointing it toward a cold space background (i.e., no stars, planets, targets in the seeker field of view). Upon completion of the calibration, the vehicle is oriented toward the target line of sight, and a roll maneuver is done to allow an alignment of the third stage and KW inertial measurement units (IMUs). Information on the KW position and velocity, along with the target position and velocity, is passed to the KW in preparation for KW ejection and flight.

Approximately 24 s prior to intercept, the KW is ejected and the SDACS is ignited. This is referred to as the "terminal" phase of flight. The SDACS's gas generator uses a solid propellant and four nozzles placed near the vehicle center of gravity to provide a divert force to maneuver the KW (Fig. 2). Six nozzles at the aft end of the KW provide attitude control. The sustain grain of the gas generator is ignited initially and provides a limited thrust to maintain steerage. This grain must burn until intercept of the target, thereby limiting the flight time of the KW. Once the IR seeker acquires the target, a second solid grain is ignited to increase the thrust level for approximately 10 s. This provides sufficient thrust to divert the KW to a collision course with the target. After the divert pulse burns out, the sustain grain continues to burn, allowing small corrections to the KW flight path. A third grain is ignited just prior to KW impact to again increase the thrust level to allow the KW to maneuver to impact the target at the most lethal spot (i.e., the position to destroy the target warhead), referred to as the lethal aimpoint.

A series of nine flights is planned as part of the ALI Program to demonstrate the ability of the NTW systems to intercept a ballistic target during exo-atmospheric flight. To date, four SM-3 flight tests have been conducted to demonstrate the readiness of various NTW systems: control test vehicle (CTV) 1 and 1A and flight test round (FTR) 1 and 1A. The first intercept attempt will occur in 2002. In these flight tests, the target will be intercepted during its descent phase of flight (i.e., after the target has reached apogee). After successfully intercepting the target twice, the target will be modified to be more threat-representative, and a series of three tests will be performed to demonstrate the ability of the NTW System to intercept a target during the ascent phase of flight (i.e., prior to apogee). During these three tests the ability of the KW to hit the lethal aimpoint will also be demonstrated.

To perform the NTW mission, SM-3 has been designed to fly considerably higher and faster than any surface-launched missile the Navy has ever built. Figure 5 shows a plot of altitude versus Mach number for the various stages of SM-3 flight during a typical ALI test. For comparison, the speed regime of SM-2 Block IV is also shown. As can be seen, SM-3 will fly more than twice as fast and five times as high as SM-2 Block IV.

Flying at these speeds and altitudes has brought many new challenges to the SM design. Aerothermal heating is significantly increased, requiring new materials to insulate the missile components. Likewise, flight outside the Earth's atmosphere has required the development of attitude control systems for the third and fourth stages of the missile. The fact that the KW must impact the target ("hit-to-kill"), rather than using a conventional explosive warhead, has created challenges to several of the systems to provide accurate information on missile position and velocity. To increase position and velocity accuracy, SM-3 carries the GAINS, which blends information from the GPS, the ship's radar, and the missile's IMUs. The use of these new features has

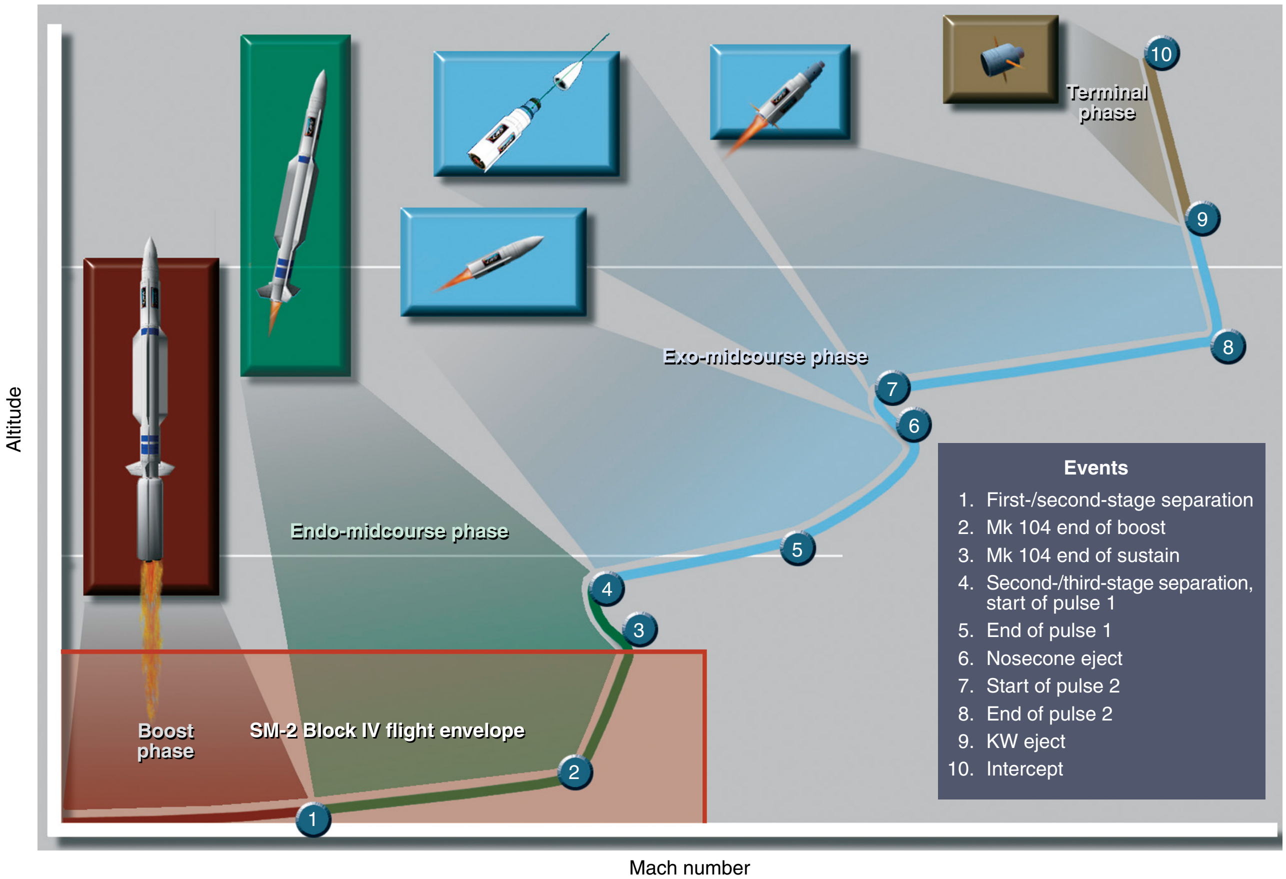

Figure 5. The ALI flight envelope.

required additional ground tests to verify SM-3 design and operation.

GROUND TEST PROGRAM

As already noted, SM-3's robust ground test program is derived from a legacy of SM testing. Some of the tests that have been added specifically for SM-3 include separation, hover, and air bearing tests. The separation test was performed to verify proper activation of all upper-stage (stages above the Mk 72 rocket motor) separating events, including second-/third-stage separation, nosecone separation, and KW ejection. Also tested were other electrically initiated devices (e.g., squibs, batteries, explosive bolts, etc.).

The hover test is intended to demonstrate KW performance in a flight test, including target acquisition. The test is to be performed at the National Hover Test Facility (NHTF) of the Air Force Research Laboratory (AFRL) at Edwards Air Force Base. The KW is initially held down and the SDACS sustain and divert pulses ignited. The KW is then released and allowed to fly autonomously. The KW computer software was modified for this test to provide a 1-*g* thrust so that the KW would hover stably at a given height. The KW was programmed to go through a series of maneuvers (side to side) during the test. A heated target is positioned at the height of the hovering KW to allow target acquisition and track throughout the flight test. The primary objective of the hover test is to demonstrate that the closed loop control will maintain the desired pointing accuracy and stay within the required body rates. The test provides confidence that the SDACS will respond as commanded and that the self-induced vibration loads created by the SDACS will not impact the ability of the seeker to acquire and track an object.

Air bearing tests were performed on both the KW and the third stage to evaluate the autopilot design. The hardware was fixed in a cradle, which allowed near-frictionless rotation about three axes. For third-stage air bearing, open loop or scripted tests were performed in which a typical ALI mission was flown. Commands were determined by the guidance computer and were turned into ACS thrust commands, which caused the missile to rotate to the desired orientation. Among the maneuvers demonstrated were nosecone pitch-to-ditch, in-flight alignment, pointing toward cold space for seeker calibration, and pointing toward the target prior to KW eject. This demonstrated proper operation of the third-stage autopilot and computer. Air was supplied to the ACS to provide thrust to rotate the third stage. In the KW air bearing tests, helium gas was used for the ACS rather than a solid propellant. In these tests the guidance loop was closed by the seeker tracking a moving target and providing information to the guidance processor, which in turn created thrust commands to the ACS. This resulted in the vehicle rotating to the proper orientation to maintain target track.

Some DVTs were performed at APL. Specifically, the GAINS was tested in the Power Projection System Department's Navigation and Guidance System Integration Laboratory (NAVSIL), and the third-stage guidance section was tested in the Space Department's thermal vacuum chamber. End-to-end system tests of all five missile computers are being performed in the Air Defense Systems Department's Guidance System Evaluation Laboratory (GSEL). These tests are discussed briefly in the next section.

GSEL Testing

The GSEL was constructed in the mid-1960s to support SM development. Its primary purpose is to provide an independent assessment of functionality and robustness of system components and computer programs for the government. It is felt that having a second team—other than the Design Agent—with different methods, equipment, and personnel increases the level of problem screening, thereby providing risk reduction for the Navy. For years, APL has performed testing of SM guidance and navigation computers as well as the computer programs. More recently, on the Missile Homing Improvement Program and SM-2 Block IVA Risk Reduction Flight Demonstration, IR seeker testing has been added.

GSEL evaluations in the past have primarily focused on endgame missile guidance in the endo-atmosphere. The SM-3 missile is unique in that it must operate through exo-atmospheric flight at speeds greatly exceeding those of other SM variants. It uses new third- and fourth-stage guidance and control. While the first and second stages are controlled as before by the AWS on the launching ship, the third and fourth (KW) stages have autonomous navigation, guidance, and control. Third-stage navigation data (position, velocity, and altitude estimates) are determined onboard using GAINS. The KW operates autonomously after being ejected from the third stage to seek, acquire, track, and divert to intercept the target. The KW must hit the target, using its kinetic energy to destroy it. All of these differences put increased demands on SM-3 operation.

A schematic of the test setup in GSEL for ALI is shown in Fig. 6. Testing falls into one of two categories:

1. Avionics suite testing, which includes first-, second-, and third-stage guidance performance; third-stage guidance integration with GAINS; and KW handover accuracy
2. KW testing, which includes KW target acquisition and tracking as well as KW navigation, guidance, and divert accuracy

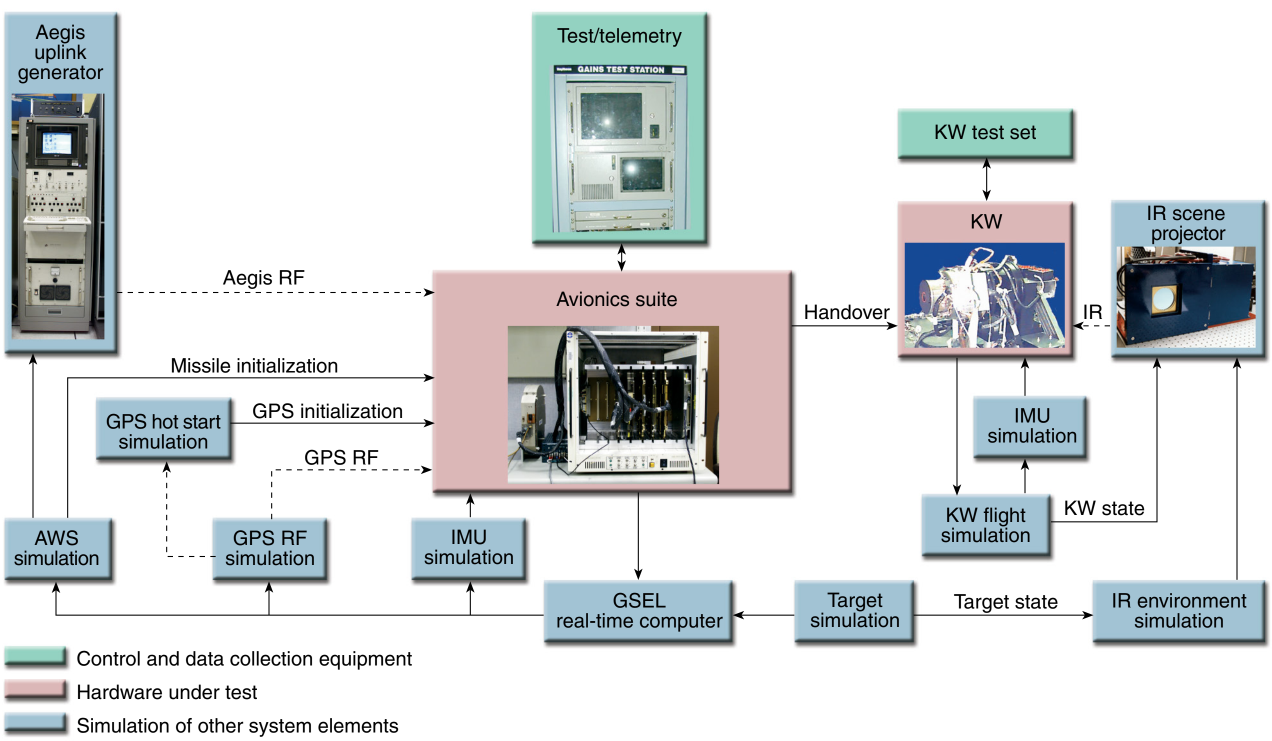

Figure 6. GSEL test configuration.

KW and avionics suite testing are performed in separate parts of GSEL to allow independent testing of each component; however, they are connected electrically to also allow a complete end-to-end testing capability as is shown in the figure.

The primary objective of the laboratory evaluation of the computer programs and hardware is twofold: (1) to reduce flight risk through an extensive characterization of nominal end-to-end system performance and (2) to identify performance boundaries of the system operating in realistic simulated flight environments. Emphasis is placed on verifying the performance of the functional interfaces between the missile and the ship. Only in special cases, i.e., when the risk is felt to be high, are the physical interfaces also tested in the GSEL. Some physical interfaces have been tested in NAVSIL to ensure that the GPS "hot start" function has been properly implemented (NAVSIL tests are discussed later in this article).

A secondary objective of GSEL is to provide a facility that is maintained through the entire life cycle of the missile (including deployment). Hardware and software are maintained in the GSEL such that if a new threat should emerge or if new countermeasures are developed, the effect on the missile can be readily determined. GSEL and NAVSIL also provide resources for flight test data analysis investigations of any flight anomalies.

Avionics Suite Testing

The SM-3 guidance section provides the capability for prelaunch round initialization, in-flight missile/ship communication, boost phase control commands, endo- and exo-midcourse guidance/control commands, and the transfer of data to the KW assembly prior to third- and fourth-stage separation. Two independent computers accomplish flight guidance and control for the first three stages. One computer, Central Processing Unit 2 (CPU2), is dedicated to controlling the guidance for the first two stages of flight, and another, CPU3, is dedicated to controlling the guidance for the third stage. The guidance section includes the avionics suite, which houses CPU2 and CPU3 as well as the GAINS Receiver Processor Unit (RPU). The GAINS RPU includes a GPS receiver and navigation processor which provides accurate inertial data. The navigation processor uses GPS, radar, and IMU data to estimate and correct for IMU misalignments and biases. The processor uses a Kalman filter to minimize processing noise.

The GSEL provides testing for actual missile guidance hardware in real time. The avionics suite maintains the latest-released version of the missile software for the CPU2, CPU3, and GAINS RPU. For components that are not included in the avionics suite, the GSEL test setup includes custom-designed real-time simulators that possess the specified hardware characteristics required to emulate the external interfaces. The major interfaces include Aegis Weapons Control System (WCS), initialization, uplink, and downlink messages; telemetry and steering control section; inertial instrument unit; accelerometer; and gyro data and power supplies. All of these interfaces are controlled by the GSEL real-time computer (Fig. 6).

The APL six-degree-of-freedom (6-DOF) simulation is a supporting tool that is needed for the avionics evaluation performed in GSEL. The simulation is a high-fidelity representation of the kinematics and functional design of the SM-3 missile. It also contains medium-fidelity models of the remainder of the weapon system, target vehicle, and environment. The simulation is used to generate trajectory files that become input files for open loop testing. Missile dynamic data are recorded from the simulation and fed into the GSEL test setup to simulate the motion of the missile. Analysis of open loop testing provides an opportunity to validate the implementation of the functional design in both the simulation and the missile software.

For closed loop testing, the 6-DOF simulation actually takes inputs from the missile software and provides dynamic output back to the missile to "close the loop." In this testing, the 6-DOF functional algorithms are replaced with the actual missile software. This allows the performance of the missile software to affect the simulated trajectory. As in the case with open loop testing, this acts as another level of fidelity in validating the 6-DOF simulation and missile software.

In addition to evaluating first-, second-, and third-stage guidance and control performance, GSEL evaluations characterize and verify the performance of the avionics suite interfaces and missile-to-ship communications. Avionics suite testing evaluates the initialization of the KW prior to ejection as well. Results of this testing also serve to validate and refine the SM-3 digital 6-DOF simulation. The avionics suite has all of the external interfaces attached to actual missile hardware or simulators. Test interfaces are available to each of the processors for software downloads, control, and monitoring. Testing is performed in both open loop (scripted scenarios) or closed loop fashion, in which the digital simulation is wrapped around the guidance processors.

Simulated trajectory inputs are derived from the digital 6-DOF simulation. The 6-DOF outputs are used as stimuli to evaluate the missile software (e.g., simulated IMU measurements). In addition to testing for missile performance, tests are performed to exercise critical algorithms and functions, especially those that are new to SM-3. Among the major areas of concentration are built-in-test processing, Stage 1 control (inertial boost guidance), Stage 2 control (Aegis midcourse guidance), Stage 3 control (TSRM/ACS guidance), Aegis target and GAINS missile state processing, message processing (initialization, uplink, and downlink), IMU data processing, KW initialization, and KW eject.

Output data from these tests are compared with digital 6-DOF results to validate the algorithms and simulation models.

A GSEL simulation of actual flight scenarios is performed to assess the readiness of the operational software for an upcoming flight. This testing examines the proper timing of events in a flight scenario and compatibility with the WCS. The flight profile is constructed with raw IMU data derived from the digital 6-DOF simulation, and from actual Aegis ship messages derived from the Combat Systems Engineering Development Site (CSEDS). These data are synchronized and fed into the avionics suite as if an actual flight were taking place, and the missile outputs are compared with digital 6-DOF results. Figure 7 illustrates sample comparisons of GSEL and 6-DOF data for a simulated flight test. Since the 6-DOF simulation is being used as the input to the software, one would expect the 6-DOF and GSEL results to compare favorably, as can be seen in Fig. 7; however, this is not always the case. When differences occur, they are due to errors in either the 6-DOF results, the GSEL setup, or the missile software. If the software is suspected, results are forwarded to the Design Agent for review. GSEL has been successful in highlighting errors in the 6-DOF data, missile software, and AWS computer programs.

In addition to nominal flight conditions, modifications to the script are made to examine performance in critical areas under off-nominal conditions (e.g., loss of Aegis uplink). From past experience, many possible failure modes have been identified which are not addressed in all of the normal testing modes. On the basis of flight scenarios, additional potential failure modes will be identified and tests developed to characterize performance under those conditions.

KW Testing

The ALI KW being tested in the GSEL has a functioning IR sensor, signal processor, and guidance processor. The unit does not include an SDACS but rather an SDACS emulator. Likewise, the telemetry antenna is omitted and signals are sent directly to the KW telemetry console. As previously noted, KW and avionics suite testing are done in separate laboratories within GSEL; however, they are tied together electrically to allow communications prior to KW eject.

The objectives of KW testing are to

- Characterize the IR sensor
- Assess coordinated IR seeker and guidance unit functionality

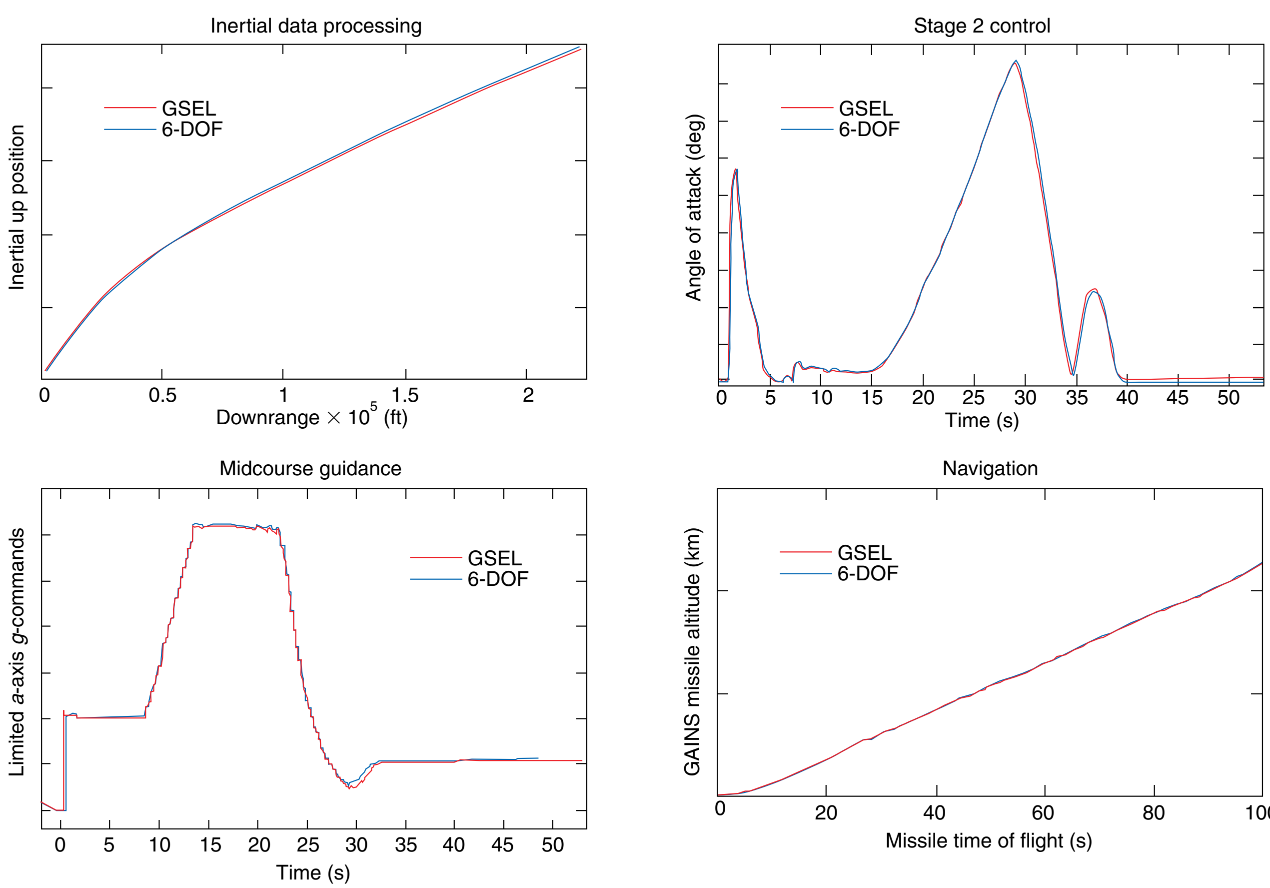

Figure 7. Sample data from GSEL avionics suite testing.

- Confirm line-of-sight stabilization in the presence of KW body motion
- Confirm KW/third-stage interfaces

APL's approach to IR guidance system testing in the GSEL is discussed in more detail by Gearhart in this issue, and only several key points are visited here.

Again, GSEL test results are intended to provide an independent functional confirmation of the KW and computer programs prior to each ALI flight test. Emphasis is on identifying potential vulnerabilities, and where appropriate, defining performance boundaries. Since the GSEL is currently the only test activity that will monitor the performance of a single KW test article over a long period, data are also collected to assess functional stability over time, in particular for the IR seeker.

GSEL KW testing is also tied closely to APL's high-fidelity digital simulation activities. For example, the GSEL characterization of the seeker optical system is used to derive and validate optical system models in the digital simulation. Viewed from another perspective, the outputs of the digital simulation are often used as inputs to the GSEL hardware-in-the-loop (HIL) simulation for open loop guidance studies. In addition, the digital simulation has proven to be essential in several cases to performing trade studies for designing GSEL test equipment (e.g., deriving data latency requirements for the HIL simulation computers).

GSEL testing involves an ensemble of test assets. Different assets are used because one type of IR target projection device may provide good fidelity for some target attributes but not for others. Specifically, a resistive heater IR display provides excellent fidelity for a growing target image during aimpoint selection and the final intercept phase of flight, but because of potential pixelization effects (i.e., spatial sampling limitations), such devices are less desirable for emulating accurate point target phenomenology. Thus simple point target generation devices are favored to provide better accuracy for functions early in KW flight that involve point targets.

In general, no single test configuration provides the highest possible fidelity emulation of relevant environmental attributes over the entire KW flight timeline. For this reason, a methodical piece-wise evaluation using a variety of tests and test devices is necessary. GSEL tests are structured on the basis of a decomposition of KW functions in flight timeline sequence (for example, seeker calibration, target acquisition, target track, etc.).

Since the SM-3 KW has a body-fixed IR seeker (i.e., no gimbals), the KW is mounted on a motorized gimbal platform for some types of tests. The gimbal platform is controlled by drive signals derived from buffered KW attitude control commands. Rather than mounting the KW on a carco table as is done in some facilities, an alternative approach being used in the GSEL is to hard-mount the KW and emulate its motion by moving the target appropriately and sending synthesized IMU outputs to the KW guidance processor.

Open loop and scripted testing in both the avionics section and the KW have been performed separately, with a simulator as the interface to the section not being tested. When the two are tested together, testing is aimed at verifying data transfer and control commands between the third and fourth stage.

Similar to avionics suite testing, the APL 6-DOF simulation is a supporting tool that is needed for the KW evaluation performed in the GSEL. The 6-DOF simulation is a high-fidelity representation of the kinematics and functional design of the KW. For the closed loop portion of testing, the simulation actually takes inputs from the KW software and provides dynamic output back to the missile to close the loop. With validation data being provided by open loop and closed loop testing, and with additional data supplied by DVTs (by the contractor), the 6-DOF simulation can be used to predict preflight performance and to perform postflight analysis.

An example of how the GSEL can be used occurred prior to FTR-1A, when Raytheon suggested changing the nominal timeline so that the KW remained longer on the third stage to allow it to image the target. Because the KW was inert (no SDACS) on FTR-1A, it had no control and therefore would tumble after KW eject. Since a target would be flown during the mission, it presented an opportunity to provide seeker data if the KW remained attached to the third stage, which had control. The Navy asked APL to assess this option. The Laboratory first used the 6-DOF simulation to show that the third stage had adequate control to maintain the target within the seeker's field of view. The simulation was then used to establish open loop scenarios for the GSEL scene projector. Tests in GSEL showed that the target remained in the field of view for a majority of the time and that the seeker was able to acquire and track the target. These results indicated that greater than 10 s of seeker imaging data should be available. On the basis of these and Raytheon's results the Navy decided to extend the timeline. On 25 January 2001, FTR-1A was flown and the KW operated as predicted by the 6-DOF simulation and GSEL. The KW acquired and tracked the target and gathered 13.5 s of IR data on the target.

NAVSIL Navigation Testing

GAINS provides position, velocity, and attitude estimates for use by the third-stage guidance and as initialization data to the KW. The SM-3 GAINS is a direct derivative of the successfully flown Terrier/LEAP GAINS. GAINS forms these estimates by combining measurements from an onboard GPS receiver, uplinked data from the Aegis radar, and an onboard IMU. The availability of highly accurate GPS measurements allows

GAINS to perform a precise in-flight alignment, thereby improving on its relatively course initialization.

The IMU is a combination of accelerometers and gyros that provide inertial motion measurements to GAINS. A navigation algorithm in GAINS integrates the IMU sensor measurements starting from an initial condition provided by two ship system measurements. This navigation solution is updated by measurements from a GPS receiver and uplinked Aegis radar data. A multistate Kalman filter corrects for estimated errors in all three sets of measurements. The resulting output is the position, velocity, and attitude estimate used by the third-stage guidance.

A system called the VLS GPS integrator (VGI) is installed on the ship for SM-3. It provides a hot start to the GAINS GPS receiver and initializes position and velocity in the navigator. To generate a navigation solution with small error, the GPS receiver must provide measurements as quickly after launch as possible. The VGI hot start allows rapid GPS satellite acquisition and track, thus generating measurements much earlier in flight. The VGI contains its own GPS receiver, which operates continuously using signals from a ship's mast antenna. The GPS receiver provides both precise time and satellite digital data needed by the missile's receiver. The information is passed into the missile via a high-speed fiber-optic cable, resulting in very high hot start GPS timing accuracy.

APL's NAVSIL is a GAINS HIL simulation and test facility. It was originally developed in the late 1980s to support the addition of GPS to Tomahawk. Over the years NAVSIL has continued to support Tomahawk evolution while also contributing to SM-3, SM-4 (Land Attack Standard Missile, LASM), Joint Defended Area Munition (JDAM), the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) spacecraft, and other programs. NAVSIL also provided risk reduction assessments for GAINS during the Terrier/LEAP Technology Demonstration. Staff analysts working with the prime contractor's team performed HIL tests to help improve the GAINS design. Predicted GAINS accuracy matched observed flight test performance.

The primary objective of NAVSIL testing is to characterize the performance of the GPS receiver and GAINS navigation under ALI flight conditions. This also includes testing VLS hot start sensitivities, GPS hold-fire issues, and GAINS navigation performance in the event that GPS signals are lost after launch. The tests identify and address technical issues associated with GPS as well as GAINS performance suitability and margin. VLS-based GPS hot start is characterized with respect to specifications and GPS acquisition under flight-representative conditions. GAINS accuracy and robustness are assessed in response to initialization errors, GPS receiver performance and anomalies, and Aegis uplink data errors.

Ground tests of the SM-3 GAINS in NAVSIL have involved assessing the performance of the supporting VGI hot start system as well as GAINS itself. The accuracy and robustness of the VGI are evaluated in many contexts. GAINS navigation error versus time in flight is evaluated by simulating GAINS with inputs like those it would receive during an actual mission. For example, hot start data are provided over a fiber-optic cable, simulated IMU output data are injected, simulated GPS radio-frequency data are generated, and simulated Aegis uplinks are inserted. Realistic sensor misalignment and other errors are included in all of these data streams. In the case of the hot start input, either actual ship equipment (a VGI and fiber-optic antenna link) or a special-purpose "hot start emulator" can be used.

Figure 8 shows the functional testbed used in NAVSIL. Data are extracted from multiple points in this testbed, allowing a thorough post-test evaluation. This ability to extract data at multiple points proved useful in troubleshooting a problem observed in GSEL. The problem was repeated in NAVSIL and the data were extracted and sent to the Design Agent, which was able to track the problem to a mathematical error in the GPS receiver. As a result, a patch was made to the GAINS software to prevent a potential flight failure.

As in the GSEL, the APL 6-DOF simulation is an intricate part of NAVSIL testing, used to provide IMU and Aegis radar data to GAINS. NAVSIL runs the trajectory in the open loop configuration and compares the position and velocity information calculated by GAINS with the 6-DOF–supplied trajectory to determine navigation accuracy. Figure 9 shows normalized example GAINS navigator performance for cases of GPS with Aegis radar uplinks. When GPS satellites are acquired, the error drops significantly for both position and velocity. For the ALI mission, GPS enhances the navigation performance, but the system has sufficient accuracy with radar and IMU alone to hit the target. This has been demonstrated in NAVSIL. However, several other tactical scenarios require GPS. For instance, for intercepts during target ascent, the nominal missile cross-range motion is small and not easily visible to the radar because of its angle measurement noise. Thus radar-only navigation accuracy for these ascent intercepts is degraded without the use of other techniques (e.g., trajectory shaping) to improve observability.

The NAVSIL was instrumental in finding a problem after CTV-1A when VGI data indicated that the GPS receiver had stopped updating satellites. The facility was able to duplicate the symptom, and the data were provided to the GPS receiver manufacturer. The software was repaired and tests were performed at APL to verify the fix.

Altitude Testing

Since SM-3 will fly outside the Earth's atmosphere, preparation is required for flight in the vacuum. At

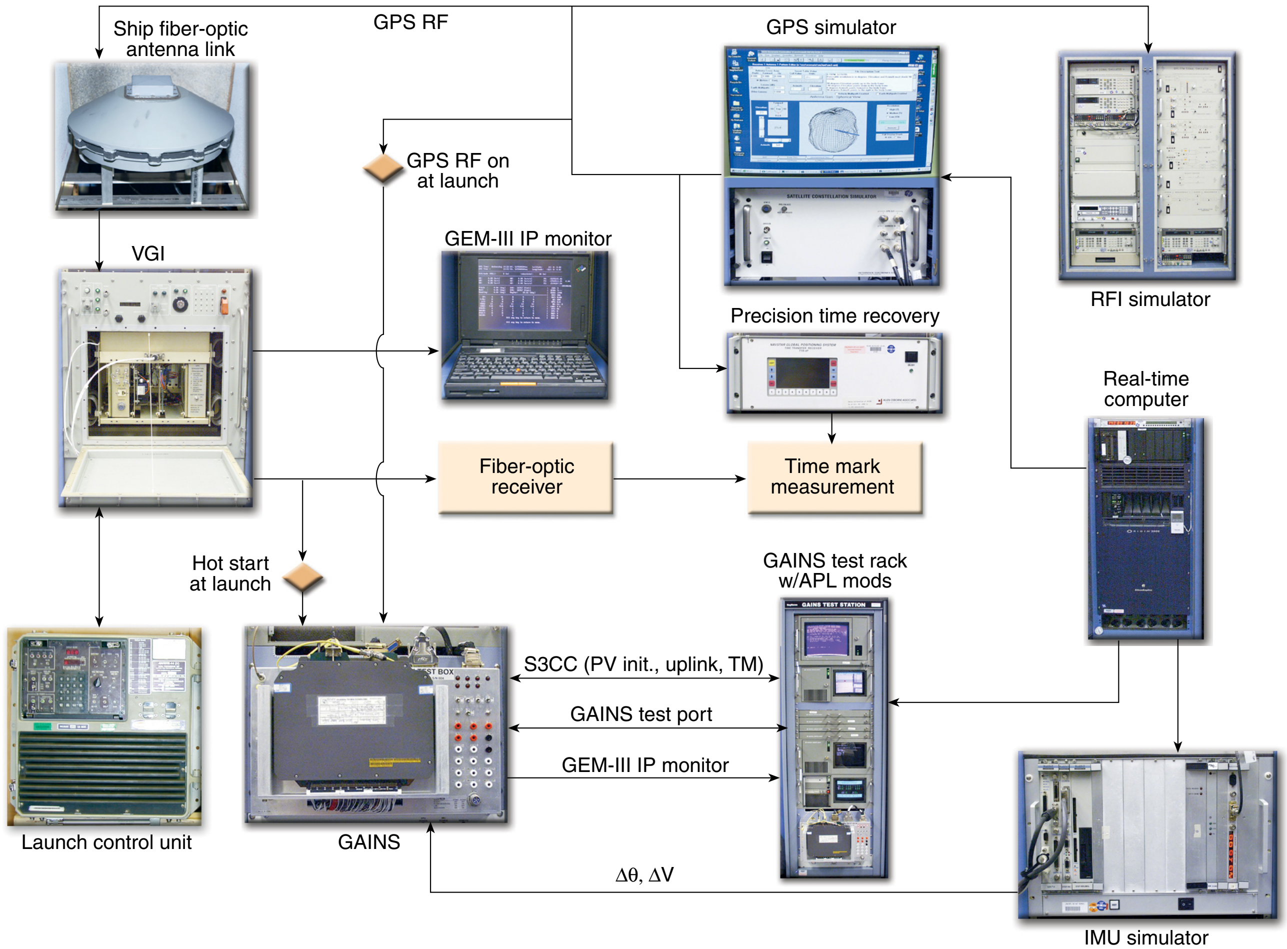

Figure 8. NAVSIL VGI hot start and GAINS test configuration.

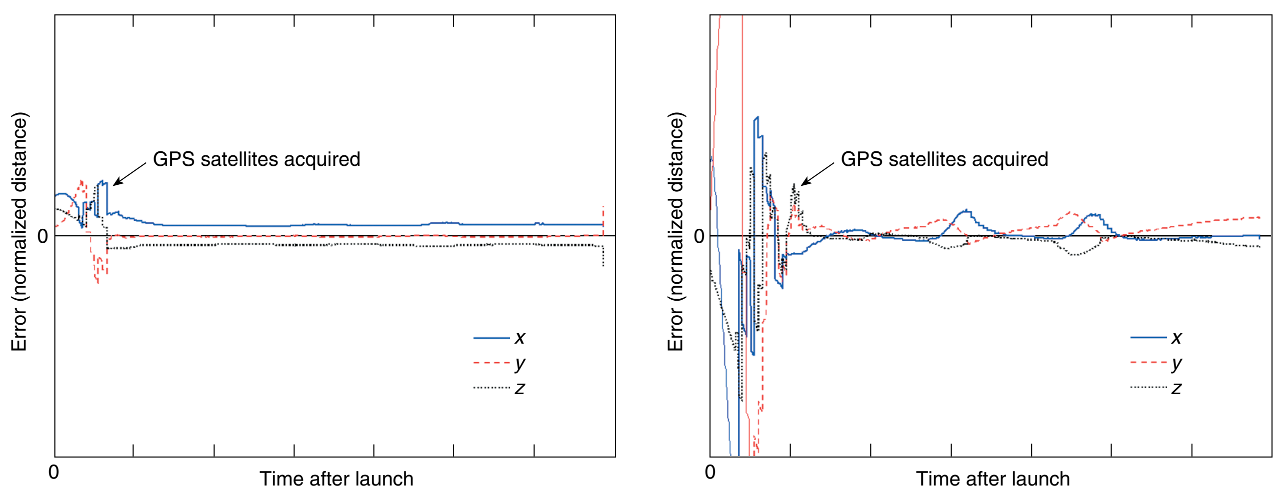

Figure 9. Position and velocity errors with GAINS.

an altitude of approximately 200,000 to 300,000 ft, the combination of low pressure and high voltage in electronic components can cause arcing due to corona effects. If any voids are present in the printed circuit boards, the vacuum will cause the void to expand, which could delaminate the board, creating a failure in a circuit. Finally, the vacuum of space will accelerate outgassing of hydrocarbons from condensable materials. For these reasons, an altitude test of the SM-3 upper-stage components was considered desirable. Although

Boeing North American performs altitude testing of the KW, their facility was too small to also include the third stage. The APL east vertical vacuum chamber was therefore used to test the guidance section.

Figure 10 shows the SM-3 guidance section installed in the chamber. The chamber was pumped down to 6×10^{-5} torr, simulating an altitude of approximately 340,000 ft. Power to the guidance section was turned off at times during the test to avoid overheating due to the long time associated with pumping the chamber down to simulated altitude (i.e., the time to pump the chamber down was greater than the typical operating time of the guidance section). Data were taken at three distinct intervals during the test. Power was turned on prior to the test to perform a baseline run; during the initial pump-down to test from launch through the maximum corona discharge region; and again once the minimum pressure of 6×10^{-5} torr was attained. Finally, a post-test baseline was taken 3 min after the chamber had reached sea-level conditions.

The guidance section performed without problem during the test. Contamination samples were taken and analyzed. Although the contamination did increase throughout the test, it was determined to be within acceptable levels.

Aerothermal Testing

In addition to the DVTs noted earlier, critical experiments were performed to ensure the design adequacy, i.e., proper structural strength and functionality, of each component. The considerably faster speeds that the SM-3 will fly (see Fig. 5) create thermal challenges for the missile structure due to aerothermal heating and force the need to include insulation on the upper stages of the missile. Components of particular concern were the nosecone, guidance section, strakes, and TSRM. APL's Research and Technology Development Center's wind tunnel was uniquely qualified to perform these aerothermal tests.

When a vehicle flies at high supersonic speeds it is heated by the compression of the air as the vehicle flies through it. This can be simulated in a wind tunnel by heating high-pressure air and then accelerating it to supersonic speeds prior to exposure to the wind tunnel model. Test cell 2 of APL's Avery Advanced Technology Development Laboratory (AATDL) uses high-pressure air heated by the combustion of hydrogen in a heater, referred to as a vitiated air heater. Makeup oxygen is sometimes added to the heater so that the oxygen mole fraction represents that of standard air. This is important for any materials that might react in an oxygen environment. Vitiated air differs from standard air in that nitrogen is replaced with steam which is generated by the combustion process (5.5 to 18.4 by mole percent for these tests). Downstream of the heater, the flow is accelerated through a converging/diverging nozzle which is sized to produce a Mach 6 flow field (see Fig. 11). The gases are controlled by computer, allowing conditions to be programmed to vary with test time to simulate vehicle acceleration. The test duration at the AATDL can be up to 3 min.

Nosecone Tests

The nosecone, developed by RMSC, provides aerodynamic/aerothermal protection for the KW during the endo-atmospheric flight. It is a composite fabricated with a graphite bismaleimide (Gr/BMI) shell with a silicon resin quartz fiber (SM8029) insulating outer layer. A thin molybdenum coating on the inside reduces thermal radiation to the KW and provides protection against electromagnetic interference. The total thickness of the nosecone is nominally 0.2 in.

Stagnation-point heating was varied with time to simulate the heating that the nosecone would experience during an ALI flight trajectory. The cell 2 facility demonstrated the ability to simulate flight conditions reasonably well through the exo-midcourse phase of flight. Because of the size of the facility, only the forward section of the nosecone could be tested in the wind tunnel. Figure 12 is a photograph taken with a standard video camera of the nosecone during a typical test at maximum heating conditions. This truncated section

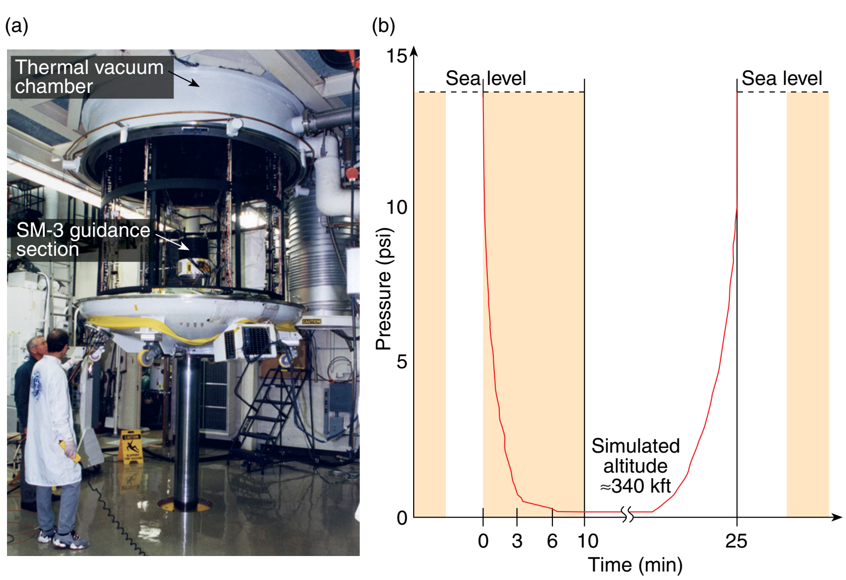

Figure 10. The SM-3 guidance section (a) under test in the APL Space Department's thermal vacuum chamber and (b) pressure profile during simulated high-altitude testing (shaded regions indicate time when guidance section was powered).

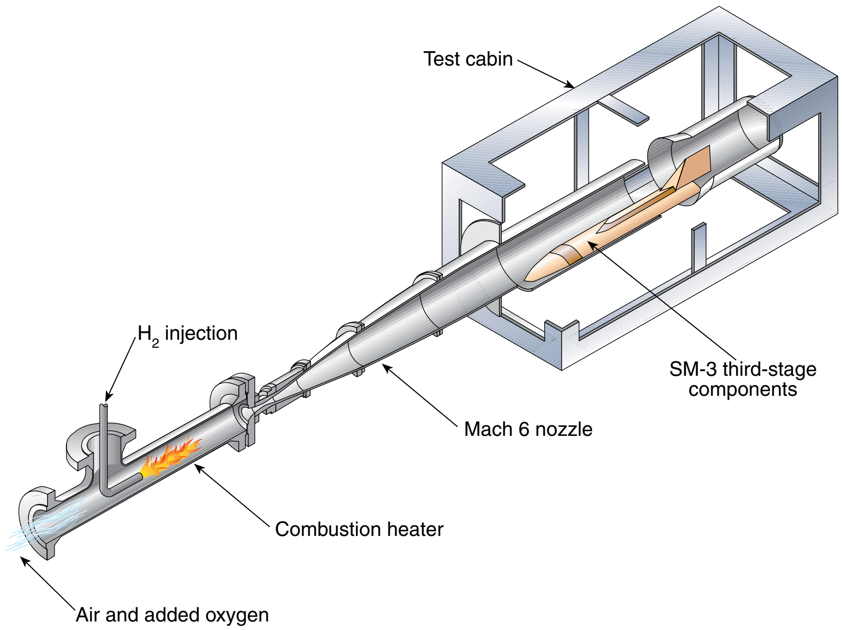

Figure 11. Schematic of the AATDL wind tunnel facility. Test setup for SM-3 third-stage insulation materials is shown.

of the nosecone contained the critical portions, which were the titanium tip, the interface between the titanium and the composite, and the point of the highest heat transfer. Heating decreases rapidly farther from the tip and therefore is not as critical to test.

Three separate test entries of the nosecone were performed during 1997 and 1998 to improve the design. In the first, 10 tests were executed to evaluate the composite nosecones. During the earliest tests the wind pattern of the quartz fiber was modified to improve its structural performance under the high-speed flow field. The cones were instrumented with up to 16 thermocouples to define the thermal environment. Deposits of condensed material were observed on the back plate of the fixture assembly for each of the nosecones tested. These deposits were determined to be a result of outgassing of the BMI resin.

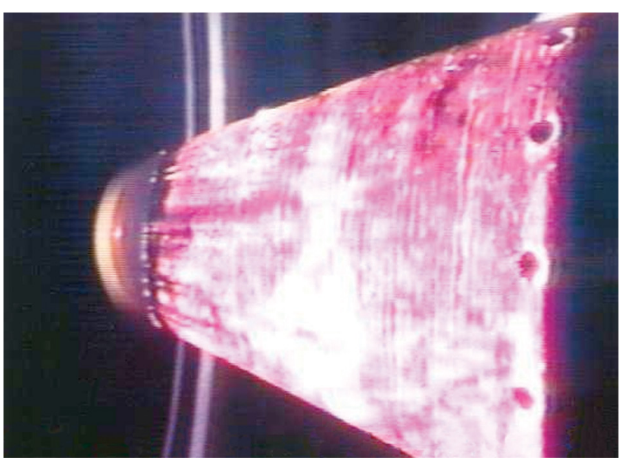

Figure 12. Photograph of the nosecone during wind tunnel testing.

Since outgassing could degrade the performance of the IR seeker in the flight vehicle, the graphite BMI coating was cured at a higher temperature (600°F instead of 450°F) to reduce it, and a cover was designed and built to protect the optics in case the outgassing could not be eliminated. The cover provides a flexible, non-airtight seal over the optical section of the KW during transportation and storage, through the endo-midcourse phase of flight, and through a portion of the exo-midcourse phase of flight. It is deployed with the nosecone at ejection (Fig 2). RMSC designed the cover and APL's Space Department fabricated several covers for wind tunnel testing as well as for the DVTs. Once the final design was completed and verified in the wind tunnel, 30 covers were fabricated by APL during the first 6 months of 1999 to be used on inert operational missiles as well as the ALI flight rounds.

In the second and third series of tests, the nosecones were instrumented to allow thermal assessment and to quantify contamination due to outgassing of the composite material. The cones were instrumented with up to 16 thermocouples to define the thermal environment of the nosecone, sunshade, and radiation shield, and the temperature of the atmosphere inside the nosecone. Three types of instrumentation were employed to measure the degree of outgassing and its effect on the seeker:

1. Optic samples were placed inside the sunshade to quantify the amount of contamination and the effect on the IR seeker optics. These samples were then analyzed using a Bomem Fourier transform interferometer to determine the effect of contamination on optical transmission in the long-wave IR.
2. Mk 21 quartz crystal microbalances (QCMs) were used to measure particulate and condensable contamination in the sunshade as a function of time for selected tests. These QCMs were also flown on CTV-1A as a final assessment of in-flight contamination.
3. A small (1.26 × 1.26 × 1.33 in.) black-and-white video camera was installed inside the cone to provide a real-time visual record of the internal environment.

The second test entry continued the development of the nosecone design to withstand the high-speed flow field and reduce outgassing as well as to develop the instrumentation necessary to quantify the contamination developed. The third entry demonstrated that the improvements made to the nosecone had eliminated the outgassing problem. It was decided that the seeker cover would still be used as added assurance against contamination.

On 24 September 1999, CTV-1A was performed with QCM sensors installed on the inert KW. Sensors were placed on the optics, where they were protected by the seeker cover, as well as on the SDACS, where they were not protected. Contamination levels were barely detectable, indicating that the outgassing problem had been eliminated.

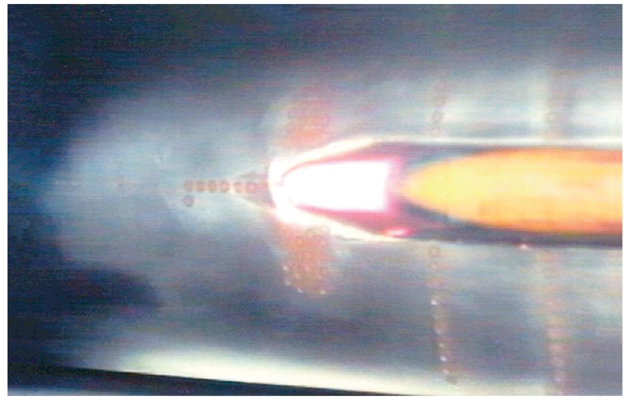

Figure 13. Photograph of the strake at maximum heating condition.

Strakes Tests

Strakes protect cables that run from the guidance section across the TSRM (Fig. 1). They are elevated from the vehicle body and therefore directly exposed to the hypersonic flow field. Two separate test entries were performed on the strakes to evaluate the designs of two suppliers. A forebody designed to simulate the guidance section and TSRM was built by Raytheon for these tests (Fig. 11). Similar to the nosecone, the strake model was stationary in the test section during testing and the stagnation-point heating rate was varied with time to simulate a flight trajectory. For the strake tests, a more severe trajectory was used than the ALI flight trajectory to demonstrate margin for the tactical design. Figure 13 shows the strake during a test at the maximum heating rate. The cell 2 facility demonstrated the ability to simulate the flight conditions reasonably well through the exo-midcourse phase of flight.

The first strake test entry was performed to evaluate three designs from two different vendors. Each vendor built three strakes, one with a solid titanium base and phenolic insulation, one with a titanium truss (i.e., cutouts in the titanium to reduce weight) covered with phenolic insulation, and one all-composite design. Thermocouples were placed at various locations within the strake to characterize the thermal environment. In addition, a sample of the cable that the strake protects was included beneath the strake. This cable was also instrumented with thermocouples. All strakes performed adequately and since the composite design was lighter in weight it was chosen. A second test entry was performed using composite strakes from each vendor, which resulted in a "down-select" to a single vendor.

Third-Stage Insulation Tests

The third stage consists of the guidance section and TSRM. The aluminum guidance section with glass phenolic insulation houses the Tri-Band antenna, which includes antennas for the GPS, telemetry, and flight termination system. The Tri-Band antenna has a duroid insulator over an aluminum shell. The TSRM interstage is a 0.1-in.-thick glass epoxy composite with a 0.187-in.-thick cork exterior insulation. RMSC built a frame to house a 70° sector of the third-stage outer shell, including a strake, for aerothermal testing (Fig. 14, left). The

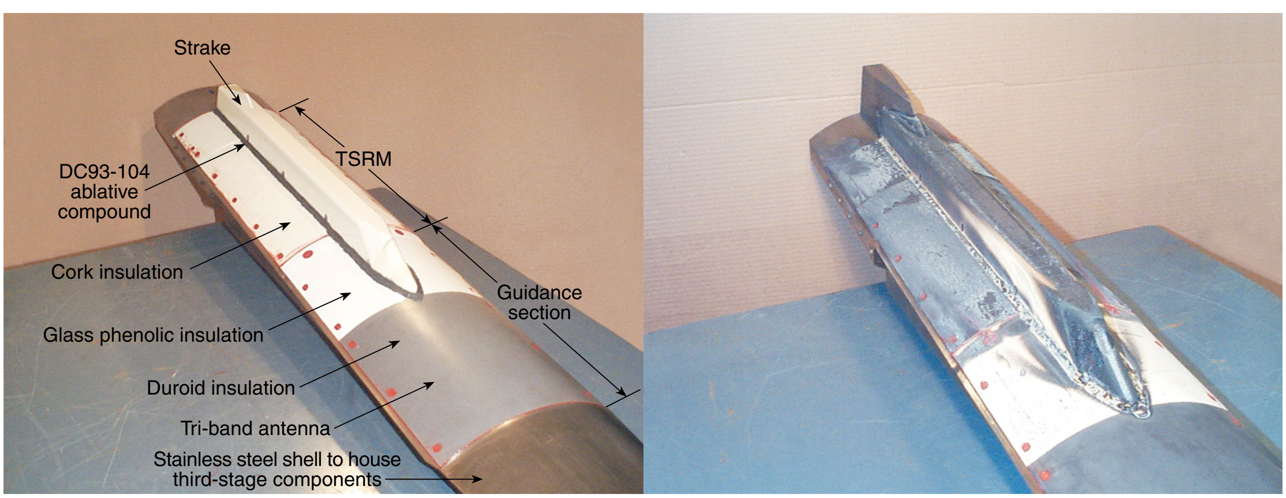

Figure 14. Before (left) and after (right) photographs of the TSRM test sample.

conditions used for these tests were the same as those for the strake tests (stressing tactical trajectory). In addition to the insulation materials, a DC93-104 ablative compound used for sealing joints on the missile was applied to seal the strake and the joints between the guidance section and TSRM.

All insulation materials successfully withstood the conditions produced by the simulated tactical trajectory. Figure 14 (right) shows the test setup after the test. One corner of the cork insulation sustained damage during the tunnel shutdown. Under this condition a shock wave translates upstream of the model, which creates a much more violent condition than would be experienced in flight.

SUMMARY

SM-3 is a unique variant of SM designed to intercept tactical ballistic missiles while outside the Earth's atmosphere. Because it flies higher and faster than any other Navy surface-launched missile and must hit the target to destroy it, SM-3 presents unique challenges. Standard Missile and its predecessors have had a long history of success, in large part due to the development of a robust ground test program to ensure adequate design prior to flight testing and deployment. The SM-3 Program has adopted this legacy test program, but because of its unique attributes several new tests have been added. APL test facilities have been used on several occasions to perform various critical experiments and DVTs. These tests have provided additional confidence in the system prior to flight and in several instances have resulted in improvements to the design.

ACKNOWLEDGMENTS: The work presented here was made possible by a group of hard working and dedicated people. The SM-3 Team at APL has made numerous contributions to the program in design evaluation, test and evaluation, preflight predictions, and postflight analyses. The author is truly indebted to this team for their efforts. Several people provided ideas, figures, and words for this article and merit recognition: Scott Gearhart, Ron Griesmar, James Johnson, Tom Johnson, George Stupp, Tom Wolf, and Dave Zotian. Raytheon Program Managers Rosemary Badian and Mike Leal are acknowledged for their continued support of GSEL and NAVSIL. The author wishes to express his appreciation to Navy SM-3 Project Manager Clay Crapps for his continued backing of the program at APL.

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