Evolved Seasparrow Missile Program

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The multinational effort to develop and field the Evolved Seasparrow Missile is nearing completion. The effort, supported by a consortium of the United States and allied nations, is a significant improvement to the existing Sparrow Missile. It will provide the fleets of these nations with an anti-missile capability against existing and projected threats that possess low-altitude, higher-velocity, and maneuver capabilities that stress present systems. This article traces the Evolved Seasparrow Missile's development from early definition efforts through engineering and manufacturing development into production transition and completion of the present at-sea developmental and operational testing that will prove its capabilities to support consortium fleet missions.

PROGRAM BACKGROUND

The NATO Seasparrow Consortium grew out of a unique Memorandum of Understanding first signed 34 years ago by the United States and three NATO allies to develop and field a state-of-the-art shipborne self-defense system to counter the threats to their navies posed by anti-ship weapons.[1] The sinking of the Israeli destroyer *Elath* in 1967 by an anti-ship missile provided even more impetus for the NATO Seasparrow program, and additional countries joined the consortium, which now has 13 members. The number of deployed systems has grown to 74 systems on four U.S. Navy (USN) ship classes and 81 systems on 19 ship classes of the other consortium navies.

The NATO Seasparrow Surface Missile System (NSSMS) used a variant of the AIM-7 air-launched Sparrow (designated RIM-7) with folded wings, modified for launch from a shipboard launching system.[2] The RIM-7, while designed to counter the threats of the 1970s, was limited by rocket motor size in its ability to meet the evolving threat. At the 53rd NATO Seasparrow Project Steering Committee meeting in Troms∅, Norway, in April 1991, the NATO Seasparrow Project Office (NSPO) presented a proposal to build an Evolved Seasparrow Missile (ESSM) (Fig. 1) for improved performance against very fast and maneuvering low-altitude threats.[3] This kinematic improvement would be accomplished by adding a rocket motor of increased diameter to the existing smaller-diameter missile seeker. The ESSM would be capable of quick start, provide the ability to receive missile guidance and head-pointing orders by either S-band or X-band transmission, and ensure compatibility with all existing NSSMS launching systems (Mk 41 Vertical Launching System [VLS], Mk 48 Guided Missile VLS, and Mk 29 Guided Missile Launching System), both vertical and trainable variants. A new warhead was later proposed and incorporated into the

Figure 1. Evolved Seasparrow Missile. The kinematic improvement of the ESSM adds a 10-in.-dia. rocket motor that can be launched from all consortium launching systems and can fit four to an Mk 41 VLS cell. Missile guidance options and an improved warhead provide additional capabilities for this newest self-defense weapon.

design. A Contract Definition Phase (CDP), to be led by APL, was proposed; seven nations initially pledged support and funds for the program.

The CDP identified a number of developmental items, among which was development of an all-up-round missile capable of home-all-the-way guidance such as Seasparrow currently uses. In addition, S-band and X-band versions of ESSM would satisfy Aegis and active phased array radar (APAR) requirements. Another line item addressed quad-pack capability for the Mk 41 VLS. All these efforts would go forward simultaneously, with Raytheon, as prime contractor, leading an international team of industries with assistance from various government laboratories and other support organizations.

Engineering and manufacturing development began in July 1995. The international industry team included a roster of companies from the nations supporting the development (by now numbering 10). Development was done under DoD-mandated integrated product development guidelines whereby Integrated Product Teams (IPTs) are given task assignments to develop various component parts of the system and are responsible for all aspects of the element, including engineering, testing, schedule, and costs. The IPTs bring together people from the various engineering disciplines as well as specialty groups (e.g., reliability, maintainability, safety, quality assurance). The membership of the IPTs included participants from the international industries as well as government and university laboratories and government representatives.

Concurrently, a System Integration IPT was chartered to ensure the integration of the delivered subsystems into an all-up-round missile and that the delivered round would integrate and function with the various ship systems (launchers, command systems) with which it was intended to operate.

A Test and Evaluation IPT was similarly developing a Test and Evaluation Master Plan (TEMP).[4] Each component of the ESSM was documented in the Prime Item Development Specification. Testing to verify each unit was specified in the Prime Item Development Specification and was further amplified through test plans and procedures.[5] A separate TEMP spelled out system-level and interface testing along with pass/fail criteria. In November 1997, the program reached its Critical Design Review and received conditional approval to proceed. Some items of high risk were identified (notably the X-band interrupted continuous wave illuminator [ICWI], which is discussed later), as were other elements of the program that the prime contractor agreed to resolve before moving on.

A series of contractor tests, including fit and form testing and blast test vehicles, gave the development team confidence that the problems were being addressed and issues were being solved. In 1998, controlled test vehicles (CTVs) and guided test vehicles (GTVs) were assessed at a land-based test site (LBTS), and in April 2001 the program entered the at-sea phase of developmental and operational testing as described next.

DEVELOPMENT

The NSPO manages the ESSM program on behalf of the NATO Seasparrow Consortium. Raytheon Missile Systems Company in Tucson, Arizona, is the prime contractor, leading a team of industrial partners from the participating nations. The Naval Air Warfare Center Weapons Division, China Lake (NAWCWPNS/CL), is the technical direction agent. In its role as technical advisor to NSPO, APL has performed special engineering investigations and analyses as directed by the NSPO and has served on several IPTs, especially as they relate to system integration.[6] APL's role in X-band and S-band development and integration is delineated later.

During the CDP, APL developed a study plan that outlined feasibility studies to delineate the ESSM design.[7] NAWCWPNS/CL undertook studies that focused on the nonforeign elements of the guidance and control sections. Various contractors looked into problems of launcher compatibility. The Laboratory, in support of the CDP, provided recommendations to the Aegis Program Office, which identified Aegis Combat System communication link requirements for the U.S. version of the ESSM S-band variant. APL also investigated X-band transmission feasibility and compatibility. Length and weight restrictions were identified, and after extensive weight, moment, and mass property analyses, APL advised the NSPO and Aegis Program Office that the Mk 41 VLS could accommodate four ESSMs quad-packed into a single cell of the launcher.

Early in engineering and manufacturing development, APL was tasked to evaluate the status of aerodynamic model development for ESSM. Upon examination of the wind tunnel Phase I aerodynamic stability tests, it was concluded that the aerodynamic database was inadequate to develop a high-fidelity, fully coupled six-degree-of-freedom (6-DOF) aerodynamic math model. The risk of potential flight failure could occur with the existing limited roll angle, tail deflection, and Mach number coverage over the intended flight regime. The NSPO accepted APL's recommendations for additional (Phase II) wind tunnel testing to mitigate the aerodynamic model risk status. The Laboratory worked with Raytheon to design a test matrix and participated in testing at the National Technical Systems' wind tunnel facility in Rye Canyon, California. In acquiring this additional aerodynamic data, the issue addressed was control-induced cross-coupling by testing with more tail combinations and finer Mach number increments across the speed regime. APL also recommended that Raytheon incorporate modeling characteristics to account for asymmetric vortex shedding during pitchover and mid-speed Mach range, as well as for rocket plume interactions.

CTV and GTV launches were planned from the Desert Ship Launch Complex at White Sands Missile Range (WSMR). In its continuing WSMR role in the Missile Systems and Combat Systems Development Group, APL worked with the Naval Surface Warfare Center, Port Hueneme Division, and with Raytheon to design the software to control these early test flights. APL also worked with WSMR Range Safety and Targets personnel to set up the testing and contributed to Test Readiness Reviews. Several blast test vehicles showed the feasibility of firing from each of the several launchers. The first CTV was fired successfully from the Launch Complex on 17 September 1998. Control actuator assemblies and autopilot design were the principal engineering challenges to overcome during early flights. An early CTV test flight is shown in Fig. 2.

During the flight test program, range data suggested that radome failures had occurred on CTV-2, GTV-2, and GTV-3. A Failure Investigation Review Board (FIRB) was convened by NSPO in August 2000 to determine the root cause of these failures. The FIRB was chaired by Raytheon and directly involved staff from NAWCWPNS/CL, NSWC/Carderock Division, and APL.

The ESSM radome is made of Pyroceram 9606, a glass ceramic material cast and fired by the Corning Corporation, Corning, New York. Two different processes have been used to finish the radome blanks, one developed by the Raytheon Company at their Bristol, Tennessee, facilities, and the second by Corning at their Canton, New York, facility. These two finishing processes produce radomes that are geometrically similar except for significant details at the radome tip: Raytheon-finished domes feature a monolithic inner surface that is ground with fixed abrasive wheels, whereas the Corning surface is lapped with a silicon carbide slurry and metal lapping tools. The Corning design is not monolithic: a small hole is drilled at the tip to admit the lapping compound, and a Pyroceram tip is installed with ceramic adhesive. The lapped surface is significantly smoother than the wheel-ground surface produced by Raytheon. When the radome is subjected to the rapid aerothermal heating that occurs during boost phase flight, the resulting stress distributions in the radome tip depend on the significant geometric differences.

Figure 2. Controlled Test Vehicle 3. The ESSM is launched from an Mk 41 VLS in a quad-pack configuration. This will be the primary launching system for ESSM aboard several consortium ships, including Aegis.

APL's analysis of the Raytheon design showed that the principal tensile stress acted directly across the rough circumferential grinding marks, which would result in a relatively low ultimate strength. For the Corning finishing technique, the direction of principal tensile stress was aligned with the much smoother finishing marks, which should produce a strength more reflective of the intrinsic material, and not due to the damage done to the surface by coarse grinding. APL also analyzed the radome-to-missile attachment area, which had been suggested by Raytheon as a possible weak area; this analysis indicated that the attachment region was not being overstressed. The APL structural analysis established a firm basis for estimating the root cause of the three ESSM flight failures as radome tip thermal shock of rough-ground Raytheon finished units. Of significant interest is that all three of the failed radomes were of the Raytheon coarse finishing process.

APL proposed to validate the analytic conclusions by subjecting tactical hardware to overly stressing thermal conditions in a well-instrumented ground test. Raytheon delivered 10 tactical versions of the ESSM radome, equipped with attachment sleeves and thermal stress instrumentation. The 10 units were divided evenly between the two finishing styles. APL developed and carried out the experiments using the National Solar Thermal Test Facility, which is owned by the Department of Energy, located on the grounds of the Kirtland Air Force Base, Albuquerque, New Mexico, and operated by Sandia National Laboratories. ESSM radomes were mounted at the focal point of the solar furnace behind a remotely activated, water-cooled shutter. Upon command, the shutter opened rapidly and the radome was suddenly exposed to the high radiant heat flux. The radomes were painted black to assure the most rapid possible absorption of the solar energy onto the outer surface. Thermal stresses under these conditions peak in about 4 s, at which time the inner wall of the radome experiences maximum tensile stress but very little thermal rise.

All of the radomes tested were fractured, and most of these failed in the tip area. There was a clear distinction between the failure stress level of the Raytheon-finished radomes and those finished by Corning, with the latter being the most capable. The test arrangement allowed the fractured pieces to be retrieved and subsequently inspected microscopically. These inspections showed that the Raytheon radomes failed because of grinding flaws at the inner surface. For the Corning-finished radomes, the failures were seen to originate at locations within the tip material, specifically not associated with a surface flaw. These most telling results about where the critical stresses act, coupled with the signals produced by the instrumentation, both correlated very well with the pretest predictions. Consequently, APL recommended that only Corning-finished radomes be used for ESSM. Subsequent GTV flights were successful.

The numerical models were used by Raytheon to predict worst-case flight radome responses over a wide variety of target intercept points. In all cases the stress predicted fell below the ultimate strength demonstrated from the solar furnace tests for Corning-finished units, although the margin of safety was somewhat below the value of 1.25 commonly used. APL also urged Raytheon to improve the thermal shock screening procedure used for all radomes. Previously, the thermal shock screening conducted by Corning was calibrated to approach the much lower Seasparrow levels; alterations were made by Raytheon and Corning to raise the levels more closely to ESSM levels. Overall system reliability using Corning-finished radomes, subject to the augmented thermal shock screening, is now estimated to be above 0.98.

In 1996, the NSPO embarked on a program to upgrade the NSSMS that encompassed new consoles, a new signal data processor, hosting of the NSSMS computer program in distributed microprocessors, and a new solid-state transmitter. Elements of the Rearchitectured NSSMS (RNSSMS) were available during the timeframe that ESSM was to undergo technical and operational testing on the Self-Defense Test Ship (SDTS) in the spring of 2001. APL had previously installed remote systems on the SDTS to operate the Target Acquisition System and NSSMS and had led the effort to test the Ship Self-Defense System and Rolling Airframe Missile Block I Guided Missile Weapon System onboard the SDTS (see related articles, this issue). A decision was made to bring the first production RNSSMS onboard the SDTS and use it to fire the ESSM during at-sea testing.

The Laboratory advised the NSPO that a Multi-Sensor Integration and Tracking System (MSITS) specially tailored to the sensor suite of the SDTS would ensure the timely detection and designation of tracks to ESSM. APL worked with the ESSM At-Sea Working Group to configure the combat system and with the ESSM Scenario Working Group to perform predictive analysis of the planned firings. Several combat system configuration options were considered. The configuration that most optimally incorporated the SDTS sensor suite and supported the ESSM schedule was one that integrated the Ship Self-Defense System and SWY (RNSSMS and Target Acquisition System) combat systems via the MSITS (Fig. 3). RNSSMS ESSM modifications included automatic cross-coupling and slaving capability to maintain tracker/illuminator illumination on target during multipath fades and composite track formulation that provides best-quality track data. These improvements in combat system integration translates into improved missile support.

With a successful CTV/GTV test series accomplished, the ESSM program began at-sea testing on the SDTS with the first firing on 5 April 2001, followed by a second firing on 13 September 2001. These developmental and operational tests were designed to demonstrate ESSM in sea-based firings against stressing targets using production-representative missiles. The operating environment is realistic in terms of the conditions expected during usual Fleet operations. These first tests exhibited missile flight anomalies that are currently being investigated by an analytical team that includes APL. However, the MSITS was shown to have properly correlated and combined sensor data to provide accurate initial designation and illumination support for the entire engagement.

X-BAND ICWI DEVELOPMENT

The APAR is being developed by The Netherlands, Germany, and Canada and is intended to be fielded

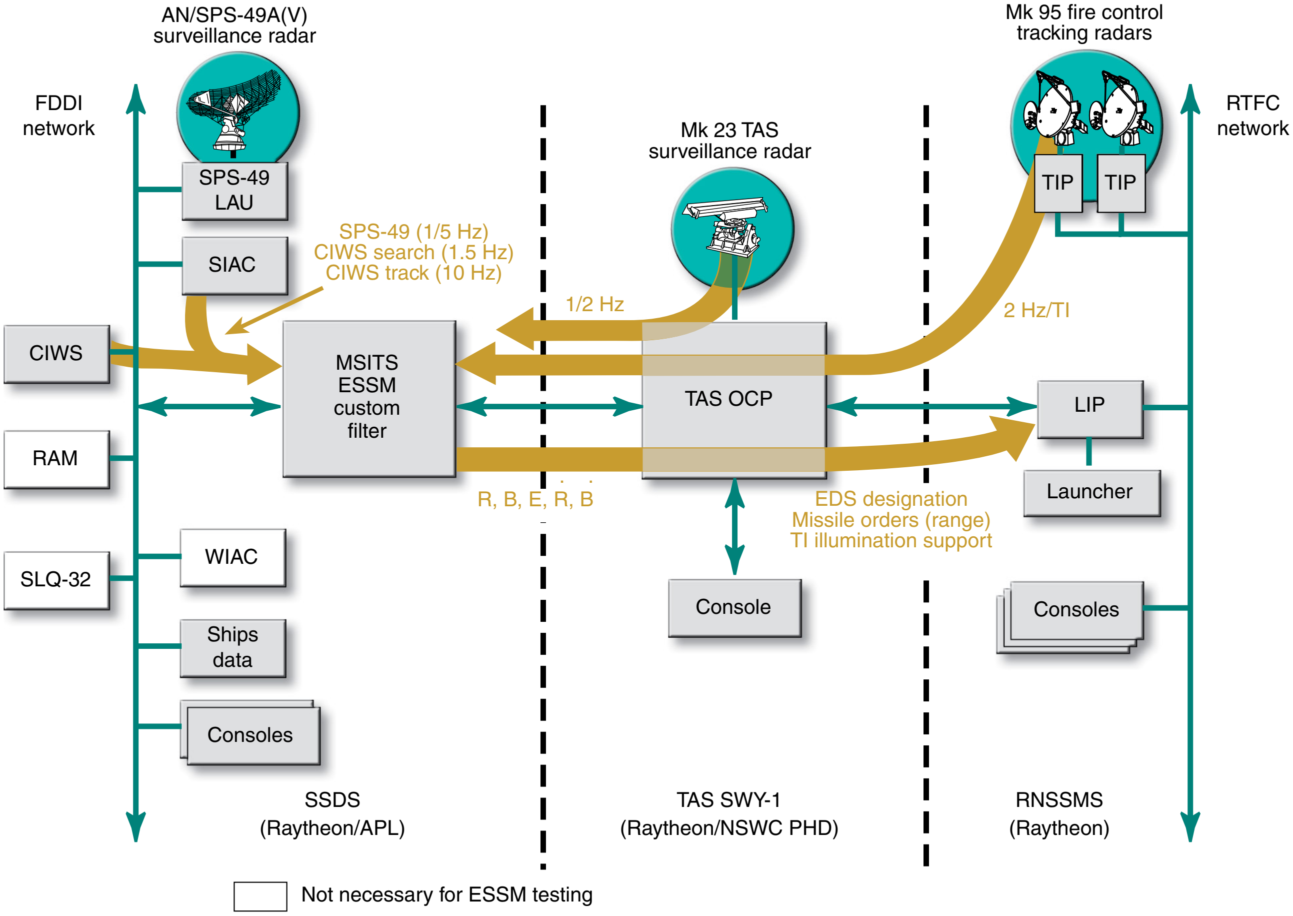

Figure 3. Self-Defense Test Ship Combat System configuration. A series of test and evaluation firings against stressing targets will verify operational suitability of the ESSM for Fleet introduction and full-rate production decisions.

aboard their newest and most capable ships. It has the ability to acquire several threats and simultaneously direct and provide illumination to multiple ESSMs (as well as Standard Missiles) to intercept those threats. In particular, The Netherlands on its L-class frigate and Germany on its F124-class frigate will combine this equipment along with the Mk 41 VLS, SIRIUS Infrared System, and new distributed command and control elements to achieve a total anti-air warfare (AAW) capability unique among consortium navies. At the request of the NSPO, APL had worked with the Dutch, German, and Canadian navies and with competing industries during the CDP to define X-band ICWI requirements. The resulting document was provided as government-furnished information in the contract as guidance for the X-band ICWI development.[8] During Critical Design Review, the Executive Panel noted that ICWI development was not only lagging behind the other elements but also that several high-risk factors were still identified that had not been satisfactorily addressed. The prime contractor put additional efforts into a plan to field the ICWI-capable ESSM in time to meet the critical schedule of the APAR countries.

The APAR program identified the need to perform a comprehensive set of tests to prove the compatibility of the APAR/ESSM interface. APL had already provided planning for APAR and Standard Missile ICWI Program (SMIP) interface testing for these ship classes. That testing would culminate with a series of Captive Carry flights of the Standard Missile guidance hardware and software in a mechanical pod carried under the wing of a Learjet. The Program Management Team overseeing the integration effort of these ships expressed the need to provide a similar program of integration studies and Captive Carry flights for APAR and ESSM. APL formulated a plan whereby the Standard Missile and ESSM Captive Carry flights could be coordinated and performed during several coincident time periods from 2000 to 2003 for an overall cost savings in aircraft services and contractor support needed at the LBTS in Den Helder, The Netherlands, and first-of-ship-class testing in Wilhelmshaven, Germany. Specific objectives of the program are to exercise SMIP seeker components and ESSM guidance and transition section components and to verify the compatibility of APAR ICWI and uplink interfaces in applicable guidance modes and guidance phases with SMIP and ESSM under real-world environmental and electronic countermeasures conditions. APL provided a detailed Captive Carry Test Plan for a coordinated approach to these tests and chaired a combined Captive Carry Working Group to address flight planning, buildup of electronic pods, data reduction requirements, and environmental assessment. Figure 4 illustrates the ESSM pod configuration on the Learjet.

The first of the planned ESSM/APAR Captive Carry tests, designated CC1, was held in July 2000 in The Netherlands. APL conducted flight operations out of the Valkenburg Naval Air Station using the ESSM pod developed jointly between NAWCWPNS/CL and APL and Learjet services provided by Flight International under subcontract to APL (Fig. 4). The APAR LBTS in Den Helder contained the engineering development model of the radar and the AAW computer systems. The Laboratory was responsible for developing and operating the instrumentation equipment and software on the Learjet to control the pod and record the telemetry signals from it. As part of this effort, APL produced a limited real-time telemetry display for ESSM and built a system to initialize the missile using data from a wireless link to the AAW system. In addition, APL provided the test conductor using the test plan developed earlier for both SMIP and ESSM Captive Carry testing, the same aircraft, and some of the same instrumentation and personnel.

The objectives of CC1 included verifying that (1) proper uplink communications existed between APAR and the missile, (2) the illumination waveform was within the specifications, (3) the missile's rear receiver could synchronize to the ICWI waveform and transition into the terminal homing phase, and (4) the target could be tracked in clutter using the APAR waveform for illumination. Nine flights of about 3 h each were conducted over a 1-week period. About 117 simulated missile engagements conducted were considered to be valid by the data analysts. Because of limitations of the ESSM software available at the time of the test, the test objectives were only partially met. Target tracking was disabled in the missile software delivered by Raytheon for CC1, but it was still proven that the APAR uplink and illumination waveforms were correct. During technical review meetings in the months following the test, trouble reports were produced for all of the anomalies that were observed, and a number of software glitches have been fixed. The second Captive Carry test will provide the opportunity to test these fixes with full target tracking implemented and to add other system components such as the missile interface cabinet into the equation.

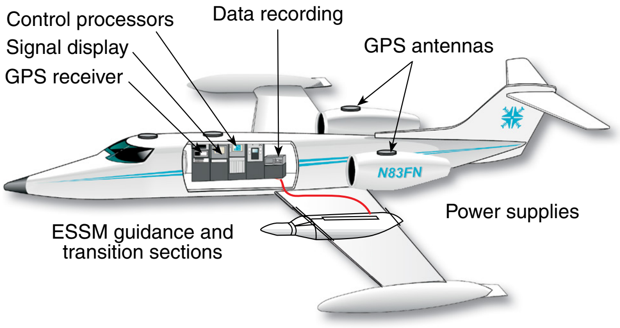

Figure 4. Learjet configuration for Captive Carry testing. The ESSM guidance and transition sections were repackaged into a pod carried beneath the wing of a Learjet. These were flown at the LBTS in Den Helder, The Netherlands, to verify compatibility of APAR ICWI and uplink interfaces with ESSM.

S-BAND AND CONTINUOUS WAVE ILLUMINATION VARIANT

In 1993, the Aegis Program Technical Director became the primary USN office for the integration of a USN surface combatant self-defense missile system. As a result, the APL Aegis Program Office provided technical guidance toward full integration of the Aegis Combat System with the NSPO-developed ESSM. Accordingly, the Aegis ESSM variant for the USN is fully compatible with existing Aegis Combat System and VLS interfaces.

The S-band variant of ESSM, designed for use with the Aegis Weapon System (AWS), uses an S-band transceiver that allows it to receive midcourse guidance commands from the Aegis SPY-1D S-band radar and transmit missile status information back to the ship. In addition to the difference in operating frequency, the S-band variant differs from the X-band ICWI variant in using X-band CWI supplied by the Mk 99 CWI Fire Control System during the missile terminal homing phase of flight. It is currently the only variant scheduled for use in USN ships and is scheduled for deployment on Aegis Flight IIA destroyers, beginning with USS *Shoup* (DDG 86). Three S-band rounds have been successfully flight-tested at WSMR, and preparations are under way for TECHEVAL and OPEVAL firings from USS *Shoup* in fiscal year 2003.

In a major upgrade to the Aegis Combat System, Baseline 6 Phase III is being readied to support the use of ESSM. As technical advisor to the Aegis Program Office, APL was tasked with assisting Lockheed Martin, the combat system design agent for Aegis, with overall missile integration with the AWS, ensuring compatibility of the Aegis command guidance system with the U.S. variant of ESSM, and developing the Weapon Control System selection logic, Fire Control System logic, salvo spacing policy, and VLS integration for Baseline 6 Phase III. To perform these tasks, APL, at the direction of the Aegis technical director, developed an AWS/ESSM 6-DOF simulation comparable in fidelity to the existing Aegis/Standard Missile 6-DOF simulations. Three years in the making, the simulation incorporates detailed models of all ESSM subsystems and adapts Aegis Combat System models currently supporting the Standard Missile simulations along with high-fidelity models of radio-frequency electronic countermeasures, multipath, and clutter. In addition to supporting the combat system development and integration work, it will support flight test scenario generation and combat system performance analysis of the Aegis Baseline 6 Phase III TECHEVAL and OPEVAL and subsequent Aegis Combat System Ship Qualification Trials. APL has participated actively in the Aegis/ESSM System Integration IPT, assisting in the resolution of combat system/missile interface issues, definition of WSMR flight test scenarios, and certification of proper operation of the Desert Ship Operational Program for the WSMR ESSM flight tests.

CONCLUSION

ESSM at-sea testing is continuing (Fig. 5). ESSM is currently approved for low-rate initial production, with full-rate production planned for 2004. The first rounds will be delivered to the Mk 41 VLS-equipped ships of the Australian Navy ANZAC class in early 2002, with at-sea firings to follow. Aegis Flight IIA destroyers, the Norwegian F2000 class frigate, the Spanish F100 class, the Hellenic Navy's Hydra class, the Turkish Navy's Track IIB ships, the Danish Navy's P550 and F354 classes, the Canadian Navy's Halifax class, and the Dutch L class and German F124 class frigates will be provided with the ESSM capability soon afterward. ESSM will provide the consortium navies with a greatly improved self-defense against anti-ship missile threats. This cooperative international effort shows what can be done when the allied navies bring together their joint capabilities to address a difficult problem.

Figure 5. ESSM firing from the Self-Defense Test Ship. This was the first at-sea launch of ESSM from an Mk 29 trainable launcher aboard the SDTS. It was also the first of a series of at-sea developmental and operational firings of the ESSM following a successful CTV/GTV test program.

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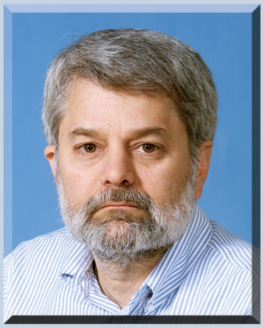

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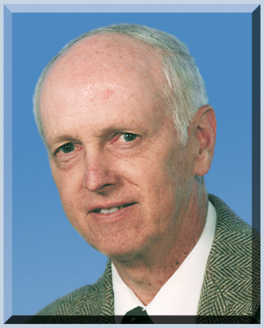

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