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FIFTY YEARS OF STRIKE WARFARE RESEARCH AT THE APPLIED PHYSICS LABORATORY

This article recounts the Applied Physics Laboratory's contributions to the field of cruise missiles and their application to strike warfare from the initial concepts through the development of the U.S. Navy antiship Harpoon and the Standoff Land-Attack Missile to the long-range Tomahawk land-attack and antiship missile variants. The first operational use of Tomahawk and the Standoff Land-Attack Missile in January 1991 made significant contributions to the neutralization and destruction of Iraqi air defense, command and control, and weapons storage facilities. The more than four decades of hard engineering work by dedicated teams from the Navy, industry, and the Laboratory that contributed to this success will be surveyed chronologically with an emphasis on the complex interactions that occurred among various mission areas.

Strike warfare or the projection of power has been a principal role of the U.S. Navy from its inception. For most of the last fifty years, the U.S. Navy has primarily been dedicated to the containment of the Soviet Union's attempts to spread communism throughout the globe. This effort has involved both the frequent show of force and, when required, the application of seapower to accomplish a specific end. Most recently, although the threat of Soviet expansionism has greatly diminished, the security of the United States and world order was threatened by the actions of Iraq. The response to this threat once again pointed out the flexibility of the Carrier Battle Group but for the first time brought into play the use of ship- and submarine-launched cruise missiles as a complement to air strikes.

In response to the significant changes throughout the world, the Navy has developed a new strategic policy termed "The Way Ahead." The policy emphasis has shifted from one of containment of the Soviet Union to one of worldwide crisis response. In the April 1991 *Proceedings*,[1] Secretary of the Navy Lawrence Garrett and ADM Frank Kelso, the Chief of Naval Operations (CNO), noted that, "Untethered from the earlier predominant concern with the global war at sea scenario, we have a new flexibility to shape our combat punch to prescribed missions and expected threats." The article also noted that greater flexibility exists in the selection of weapons for use in the application of this new policy. "Complementing carrier airpower is the formidable firepower distributed through our modern surface combatants and attack submarines. Major advances in weapons technology have brought longer ranges and greater accuracy in weapons and combat systems small enough to be employed from a variety of platforms, making it possible to disperse a significant amount of firepower. The effective employment of Tomahawk missiles against Iraq from battleships, attack submarines, cruisers and destroyers is a precursor to the multi-mission utility we must continue to emphasize in the future."

The Applied Physics Laboratory has contributed to the field of cruise missiles and their application to strike warfare from the initial concepts in the late 1940s and in the 1950s through the development of the U.S. Navy antiship Harpoon and the Standoff Land-Attack Missile (SLAM) to the long-range Tomahawk land-attack and antiship missile variants. The first operational use of Tomahawk and SLAM in January 1991 made significant contributions to the neutralization and destruction of Iraqi air defense, command and control, and weapons storage facilities and therefore played a significant role in the successful outcome of Operation Desert Storm. This success reflects over four decades of hard engineering work by dedicated teams from the Navy, industry, and APL. The history of cruise missile development is complex, for the emphasis continually shifted between strategic and tactical roles and between land-attack and antiship missions. The story could be told in a multitude of ways emphasizing each of these areas. To simplify the story we will use a chronological approach and describe events as they happened over broad periods of time. As a result, we will move across various mission areas and try to reflect the intricate synergism that occurred among the various programs and subprograms.

THE 1950s

The success of the proximity fuze program at APL during World War II led to significant new assignments from the U.S. Navy's Bureau of Ordnance. At this time, in keeping with the Navy's great concern over the air-launched antiship missile, APL's priority was the development of air defense missile systems. Though strike weapons received less attention, the potential for long-range missiles was fully appreciated, and the Bureau charged the Laboratory with the conduct of a research effort for a strategic application that became known as the Triton Program. Early studies of long-range missile technology concluded in the selection of a ramjet power plant for Triton that would propel the missile at very high altitude and at supersonic speed. This choice resulted in a synergistic relationship between the Triton and Talos air defense programs, and the feasibility of ramjet propulsion, large solid-fuel rocket boosters, and a large 48-in. ramjet combustor was quickly demonstrated. Nuclear warheads, an outgrowth of World War II, were part of every conceptual strategic long-range missile study of the period. The Applied Physics Laboratory, with an appreciation for the role of accurate delivery of ordnance gained in the proximity fuze program, stressed the importance of accuracy in minimizing warhead yield requirements and collateral damage to nonmilitary targets. Accuracy was recognized as an essential, and absence of a workable approach delayed the initiation of full-scale Triton development for several years.

Researchers conducted surveys, analyses, and experiments to provide a sound basis for assessing the guidance situation. Magnetic lines of force were considered for midcourse guidance, and anomalies in the Earth's field were examined to see if they could be used to provide a fix near the target. Visual and infrared radiation and reflection from various objects as well as the alternating current magnetic field and the electrostatic field from cities, transmission lines, and power plants were considered. Of the concepts investigated in this early period, only radio frequency beacons placed near the target by an agent provided a satisfactory solution with available technology. The tactical deficiencies, however, were all too obvious.

A British development from World War II appeared to have promise as a guidance system. The system, code-named H2S, depended on an airborne active radar to illuminate cultural and prominent geographic features; the return signal was processed to obtain range and bearing to objects in the field of scan and displayed on a cathode ray tube. The result was a "live" radar map that could be compared with a chart and used by an aircraft crew to navigate accurately even if the route to the target were obscured by clouds. The H2S-equipped aircraft would fly in a pathfinder role, dropping marker flares for the following aircraft that conducted area bombing. Consistent with the technology available, the process was largely manual. With ongoing postwar developments, automation of the navigation function soon became a reality, and radar map-matching became a leading candidate for Triton guidance. By 1958, plans were under way to develop a solid-state digital computer to accomplish map-matching—a radical departure for that time.

In other areas of technology, rapid progress was also apparent. High-energy fuels afforded new opportunities to increase range or reduce weapon size. Miniaturization of subsystems was especially notable. In Triton's early conceptual period, inertial navigators were 6 ft in diameter, and atomic warheads weighed 10,000 lbs and were similarly sized. Predictably, the Triton defined in the initial studies was enormous. The great size of the inertial navigator motivated experiments in magnetic midcourse guidance as previously described. Inertial system size and weight, however, proved to be a temporary problem. The rapid pace of improvements in inertial navigation has continued into the 1990s with laboratory products of great accuracy now emerging that can be held in the palm of one's hand.

Low-level effort continued on Triton until mid-1955. Notable progress in all technical areas encouraged the Navy to fund a full-scale effort to provide a tactical weapon. A. George Carlton provided leadership of the program in this expanding phase. The principal contractors were McDonnell Aircraft Corporation (vehicle and integration), Goodyear Aircraft (radar map matching), Kearfott (inertial navigation), Convair (ramjet propulsion), and Allegheny Ballistics Laboratory (rocket boosters). Construction of flight test vehicles was progressing well in September 1957, when the program was returned to a research phase. This phase was terminated in 1959 following documentation of an improved performance version of Triton that featured a further reduction in size.

The Triton program contributed to the rapid pace of technology advancement, some of which had broader application than just the particular usage in Triton or missile guidance. One remarkable example is in the area of signal filtering. In brief, Triton's map-matcher results were applied to its inertial navigator by a Correction Computer developed by APL. The Correction Computer was a forerunner of the Kalman filter. The next several paragraphs outline the story of this development and its significance.

In the late 1940s and early 1950s, APL had become a leader in optimal guidance and control techniques with application to surface-to-air missiles. In 1956, James W. Follin, Jr., developed the theory for the transient response of a tracker with noise and maneuver and determined the optimum time-varying gain.[2] He presented his results for a one-dimensional tracker at an Advisory Group for Aerospace meeting on guided missiles. In 1957, James E. Hanson used the calculus of variations to prove that the method was mathematically sound and extended the results to systems with acceleration constraints.[3] When the Triton problem arose, engineers recognized that little difference exists between tracking a maneuvering target and tracking randomly varying inertial system drifts, so that the basic theory applied. Richard S. Bucy extended the theory to multiple dimensions for the Triton application.

Richard Bucy and Rudolf E. Kalman collaborated on a 1961 paper[4] that had enormous impact and brought to the problem the unifying principles of state variable format and matrix algebra. The technique they described was first called the Kalman-Bucy filter, which later became known as the Kalman filter, and has been widely applied to numerous problems ever since. Some of this history was given in a 1968 book by Richard Bucy and Peter D. Joseph that was dedicated to James Follin, Jr.[5]

Other contributions included magnetic field studies and analyses that earned Alfred J. Zmuda an international reputation in the Earth sciences field. Vernon W. Brumbaugh's and Thomas G. Konrad's experimental work on ramjet diffusers was lauded by a later generation of industry researchers as being thirty years ahead of its time. James H. Walker's patented prescription for integration of supersonic airframe and propulsion systems found expression in the Concorde and, more recently, in Aerospace Airplane proposals.

Events in the mid-to-late 1950s were responsible for the cancellation of all cruise missile projects. The discovery that the Soviet Union had successfully fired an intercontinental ballistic missile (ICBM) caused concern in the United States. Up to this time, conventional wisdom in the United States decreed that ballistic missile reentry conditions were too severe for survival of a warhead. The Soviet accomplishment quickly led to successful demonstrations by the National Advisory Committee for Aeronautics indicating that warhead survival is indeed possible. At about the same time, the size and weight of nuclear warheads and inertial navigation systems were greatly reduced, and more capable rocket propulsion systems became available. These improvements led to U.S. programs to deploy ICBM's. The development of ICBM's was thought to obviate the need for long-range strategic cruise missiles.

THE 1960s

Because of the emphasis on ballistic missiles and strategic warfare, efforts on cruise missiles languished in the early 1960s. This indifference changed in 1967, however, when the Egyptians sank the Israeli destroyer *Elath* with a conventionally armed cruise missile fired from a patrol boat. The demonstrated effectiveness of Soviet antiship missiles in the *Elath* incident resulted in widespread acknowledgment of the growing threat to U.S. Naval forces posed by the Soviet Union. A new problem had been created, moreover, as the Soviets furnished client nations with antiship–missile-equipped patrol boats. In response, numerous committees and panels met to review strategies and to assess the capabilities of our defensive and offensive weapons. The groups were sponsored by Naval agencies and individual organizations. Study reports and unsolicited proposals were rife.

The Applied Physics Laboratory was represented on many of the committees and panels and contributed analyses, design tradeoffs, and risk assessment. Initially, APL's effort was sponsored by the Naval Ordnance System Command (NAVORD) and emphasized surface ship application of antiship missiles with secondary use from aircraft. Similar efforts were sponsored by the Naval Air Systems Command (NAVAIR) at the Naval Weapons Center, China Lake, California (NWC/CL), and were directed primarily towards air-launch objectives. Both efforts examined the performance of potential solutions against a variety of naval targets, including patrol boats.

The exigencies of funding during the Vietnam period led to Department of Defense and CNO pressures to develop a single missile that could be launched from both aircraft and ships and later from submarines as well; design studies indicated a single missile approach, designated Harpoon, was feasible and consistent with the demands of the Operational Requirement. The lead agency for the common missile concept was NAVAIR, and NAVORD was named the deputy.

In late 1969, NAVAIR and NAVORD formed a joint committee to conduct what is now called a Concept Exploration & Definition Phase 0 study. The Laboratory appointed James H. Walker to represent APL on the newly formed committee and to lead Laboratory activities in support of the program objectives, which were threat analysis, technology evaluation, and the preparation of missile and system design studies. Critical experiments on radar seekers were a particularly important activity in this period. Martin W. Barylski led the APL team that made a critical contribution to an understanding of radar backscattering from the sea and its effect on the selection of active radar seeker parameters. Engineers at APL designed and breadboarded multifrequency radars and instrumentation to collect sea-clutter, target radar cross-section, and radar track-point data. This equipment was installed in a World War II B-25 bomber flown as low as fifty feet over the water. The Laboratory provided the engineers who flew in the aircraft as test conductors during various test phases and played a key role in analyzing the data and in presenting the information so that it could be used for comparison of competing seeker concepts. (The value of a frequency-agile Ku-band seeker soon became apparent.) The data derived and the techniques for their use continue to provide a basis for preliminary design studies.

The radar tracking data obtained by the APL group were displayed on a TV monitor to show the seeker aimpoint. The display and accuracy were so impressive that Defense Department skeptics were quickly converted to the view that the Harpoon missile was ready for development. The Laboratory began comparative analyses of midcourse and terminal guidance concepts and seeker acquisition studies. A "red team" environment was created to exercise both the APL- and contractor-developed seekers in an electronic warfare environment. Tradeoff issues were developed by APL that clearly delineated the choices in propulsion, airframe, and launchers and illustrated the substantial benefits of a turbojet engine for the application. Several illustrations from these activities appeared in the first Harpoon Development Concept Paper. The experiments and studies were documented in a multivolume report and published by the U.S. Navy. Other contributing agencies included NAVAIR, NAVORD, NWC/CL, intelligence agencies, and several contractors.

Consistent with the report's recommendations, the Harpoon missile is a launch and leave weapon (i.e., after launch the weapon does not need the launch platform to assist in completion of the mission) that is powered by a turbojet engine and uses a conventional warhead. After launch, and until Harpoon reaches the target area, it flies a preplanned, very low altitude course controlled by a heading reference and radar altimeter (see Fig. 1). Near the target, the active radar seeker is activated and begins search. When the target is detected, the seeker locks on and guides the missile to intercept. Active radar is used because the Operational Requirement demanded all-weather operation.

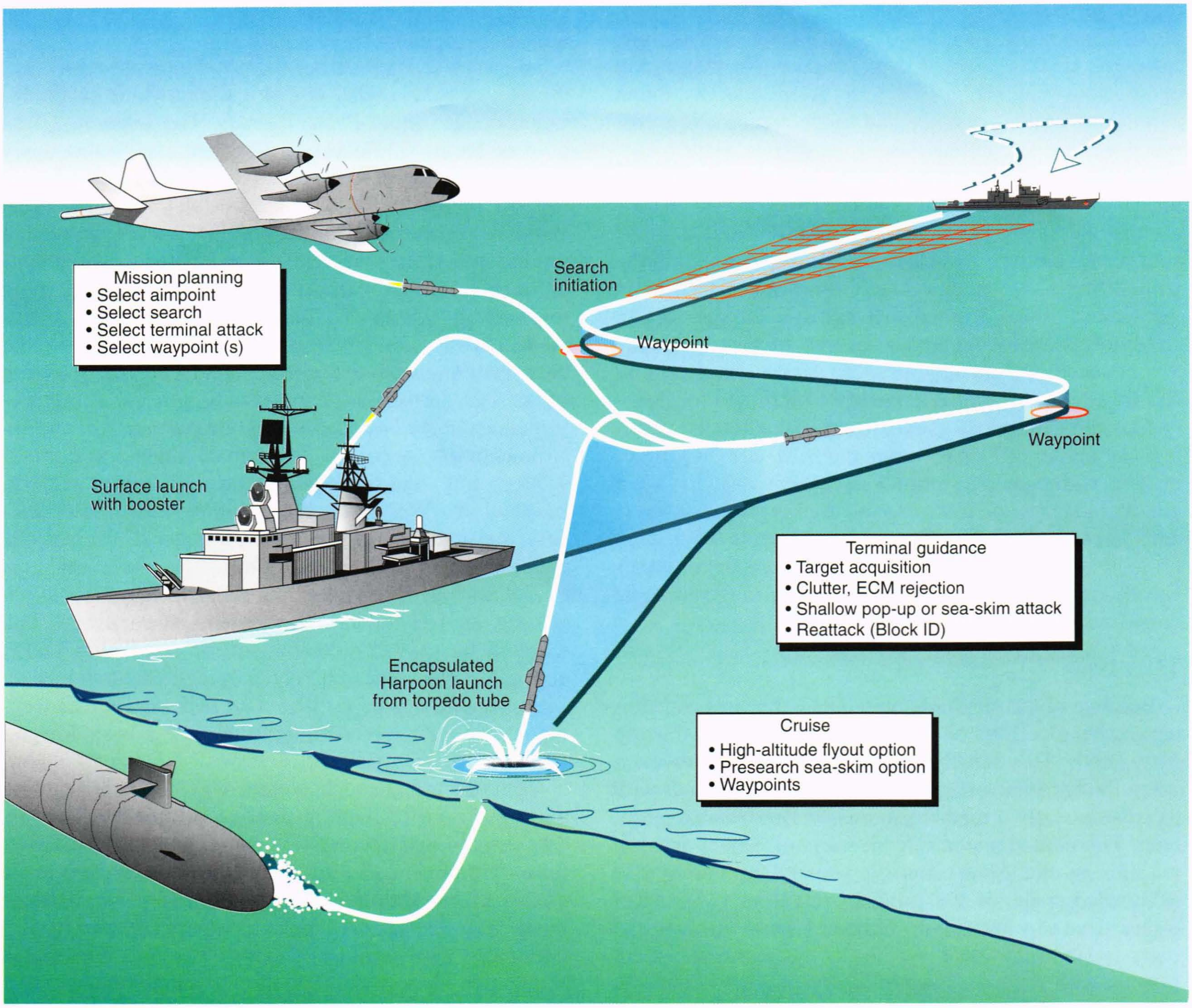

Figure 1. A simplified diagram of the Harpoon antiship missile operational concept. All three of the possible launch platforms (aircraft, surface ship, and submarine) are shown, and prelaunch mission planning (cruise and terminal phases) are highlighted (ECM = electronic countermeasures).

THE 1970s

Because of the sound technical basis developed in the 1950s and 1960s, the Navy was well prepared to move into the 1970s. This decade saw the introduction of the first tactical cruise missile (i.e., the medium range Harpoon) and the start of development of the longer range Tomahawk.

In November 1970, the Defense Systems Acquisition Review Council (DSARC) reviewed progress and gave its strong endorsement and approval for the Harpoon Design Phase. With a successful Milestone I review behind it, NAVAIR formed the Antiship Weapon Systems Project Office with CAPT (later RADM) Claude P. Ekas, USN, as Project Officer and conducted a source selection activity. The two-year Design Phase began in June 1971 with the selection of McDonnell Aircraft Corporation as prime contractor. McDonnell and its terminal guidance contractor, Texas Instruments, began development of the DSARC-approved configuration of a turbojet missile with active radar guidance.

During the Design Phase, APL conducted anechoic chamber testing of an engineering model seeker constructed by Texas Instruments. Using target generation and electronic countermeasures (ECM) simulation equipment designed and built by APL, seeker performance in both clear and countermeasure environments was determined. For a captive flight test series that was closely coordinated with the chamber testing, APL designed and constructed a special simulator to exercise the active radar seeker in ECM environments at Pt. Mugu, California. This simulator was needed because surveys and analyses showed that ECM equipment in use and under development would be ineffective against the Harpoon missile. The Laboratory also designed and built gimbaled TV equipment for the A-3 aircraft assigned to the program. The TV equipment was used to evaluate tracking performance of the seeker, which was designed and built by Texas Instruments.

In the 1970s, APL was referred to as a "friendly adversary" because the Laboratory not only created an ECM environment but assisted McDonnell and Texas Instruments in the enhancement of the Harpoon seeker's performance. The friendly adversary role has been credited with endowing Harpoon with its formidable capability against countermeasures.

The appropriate program offices in NAVSEA and NAVAIR each developed a weapons control system for employment in ships, submarines, and aircraft. Harpoon was first certified on a U. S. Navy ship in 1976. Figure 2 shows the current installations in both U.S. and allied forces. After Initial Operational Capability was achieved in 1977, Block 1A and 1B seeker changes to improve ECM capability came in rapid succession. New types of ECM equipment were designed and built by APL to simulate the continuously evolving threat. The quality of the analyses, experiments, ground and flight test support, and reporting in Harpoon's early development phase gave the Laboratory great credibility in NAVAIR. As a consequence, APL continues to play a major role in Harpoon guidance and countermeasures under the direction of Martin Barylski and Brian C. Toeneboehn.

Meanwhile, the submarine community of the Navy chartered a committee under RADM Robert Y. Kaufman to examine requirements for a submarine-launched antiship missile. The committee thought that a submarine could exploit a longer range missile than planned in the Harpoon program and that a more lethal warhead was desirable. It was also believed that submarines could accommodate the larger missile that would be needed. In early studies, the feasibility of launching this type of missile vertically from a proposed new class of high-performance submarines was of paramount interest. Some studies of launch from soon-to-be-retired Polaris submarines were also undertaken. Similar studies were supported by OP-96 but focused on surface ship needs. The Laboratory supported both efforts with design studies and analyses.

Early analysis provided by APL indicated that a Harpoon seeker could be adapted to the missile identified in these studies. The range and payload capacity of the vehicle suggested, moreover, that a second version with alternative guidance and a nuclear warhead could provide a strategic land-attack capability. The second version caught the interest of the State Department, and funds were made available through joint action with the Defense Department to the Harpoon program office to provide more detailed technical, cost, and schedule data. The APL Harpoon team led by James H. Walker made major contributions to these system concept studies and to a later extension that became a basis for the description of the Tomahawk missile system. Both antiship and land-attack versions that were compatible with 637- and 688-class attack submarines were identified in the latter phase. The antiship effort on Tomahawk was closely coordinated with the Harpoon seeker development to gain the obvious cost and schedule advantages. Roger H. Caldow used his long experience in the Harpoon program to assist in the antiship Tomahawk missile developments. A completely different guidance system was needed for the second version of Tomahawk, and APL met the challenge by applying experience from the Triton program.

In November 1972, a new program office, PMA-263, was established, and CAPT Walter M. Locke from the Harpoon Program Office was named Program Manager. Because of the good relationships established in the early days of Harpoon and Tomahawk, APL continued to provide major support to the new office.

The fundamental guidance problem was achieving the required accuracy after two- to four-hour flights. After reviewing several possible solutions, APL recommended the application of a Terrain Contour Matching (TERCOM) system in development by E-Systems. The basic TERCOM concept is shown in Figure 3. Contour maps of terrain sections enroute are digitized and stored aboard the missile. As the missile flies along, a radar altimeter measures the altitude of the missile, and a comparison is made of the resultant profile with the stored contours. A best fit is computed, and the coordinates of that position are used to correct the position indicated by the inertial system. Using the Kalman filter, the inertial navigator performance was enhanced sufficiently by TERCOM to achieve the required terminal accuracy.

Figure 2. Chart showing the widespread installation of Harpoon missiles on U.S. Navy, U.S. Air Force, and allied launch platforms.

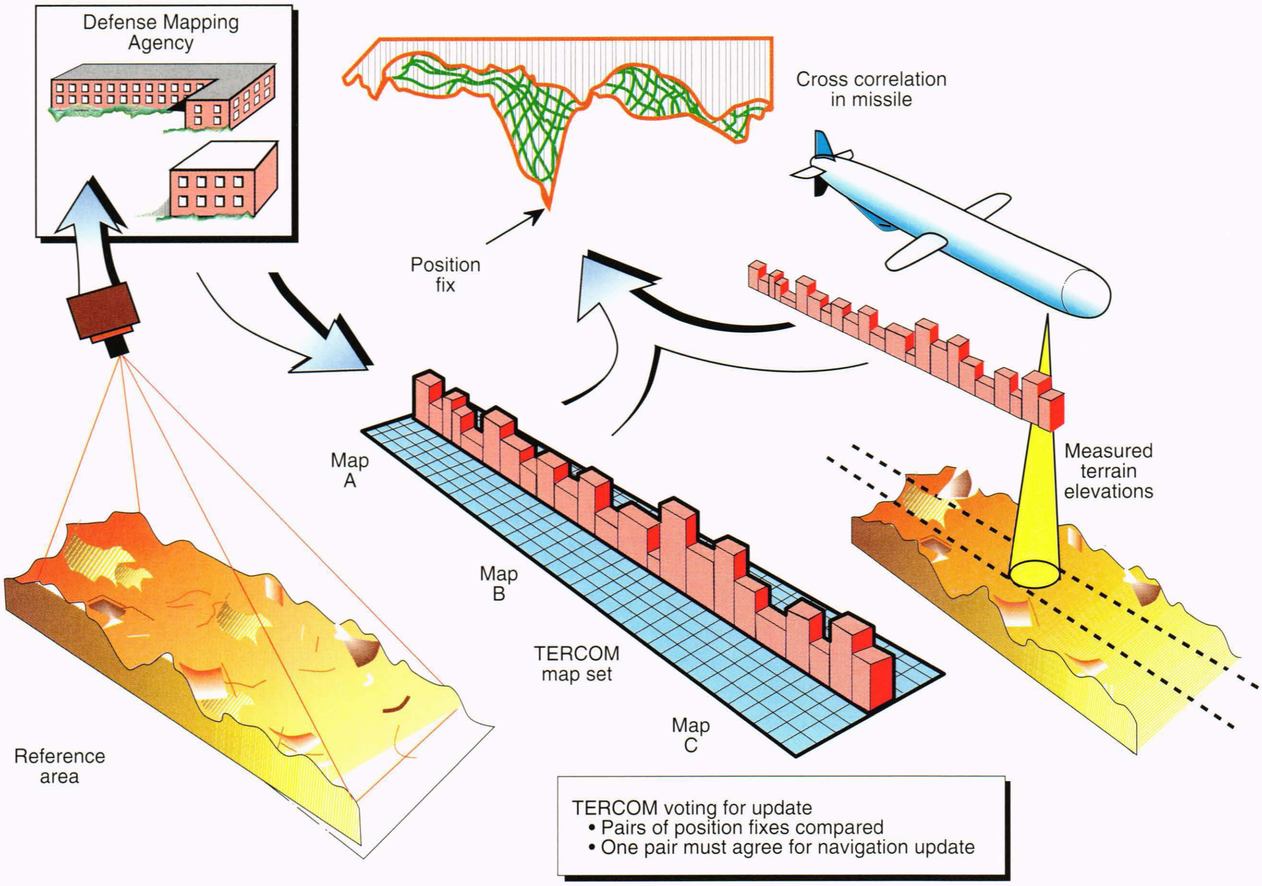

Figure 3. The Terrain Contour Matching (TERCOM) concept used in the cruise missile. A prestored map prepared by the Defense Mapping Agency is matched to the altimeter reading from the missile; then a navigation position update is computed.

The first major hurdle for this guidance system was to demonstrate mission planning using digital contour maps generated by the Defense Mapping Agency (DMA) from stereographic photographs. A breadboard guidance system was packaged in a pod to be carried over a route in New England under the wing of an A-7 aircraft. The development contractor made preflight predictions of the ability of the guidance system to select the correct match on each of the maps in the mission. These predictions were based on only a few statistics of the terrain—most importantly its roughness. William G. Spohn of APL took a different approach that involved simulating flight across many possible paths through the selected area using columns of the reference terrain matrix to represent terrain profiles collected in flight.

It was the cruise missile program's good fortune, though it hardly seemed so at the time, that the first map on the New England route was placed where it was. The development contractor and William Spohn disagreed over the quality of the site: the development contractor's estimate of failure probability was four in a million, whereas APL's estimate was about 50% because some terrain elevation profiles resembled others. As it happened, the first fix over the first TERCOM map in the first cruise missile mission ever flown was a failure when the A-7's guidance set fixed incorrectly over that New England map on 14 April 1973. Over the next year and a half, fifteen flights were made over the map, and the fixes were incorrect seven times. The importance of selecting the right sites for TERCOM maps was clearly demonstrated (a valuable lesson for the cruise missile program), and because his predictions proved so dramatically correct, Spohn—and APL—gained immediate recognition for TERCOM expertise.

Over the years, TERCOM has matured into a well-proven and extremely reliable position updating system, and APL has been responsible for much of the progress. Robert W. Dougherty developed the requirements document that not only served as a basis for DMA's product specification but defined how planners would use TERCOM maps in constructing a Tomahawk mission plan. A team from APL led by David V. Kalbaugh assisted in conducting an extensive captive test program. On the basis of the test results, and again drawing upon the expertise of William Spohn, the team developed a new method for performance prediction for use by DMA that accounted for the variation in accuracy of the source material from which the maps were made. A final improvement to these methods was made by a team led by Dennis M. Sesak that enabled more reliable maps to be produced in very smooth terrain areas. Significant contributions and leadership in TERCOM have continued and, as described later, were especially important in Desert Shield/Desert Storm.

In 1975, General Dynamics/Convair Division was selected to complete the design of the air vehicle, and APL supported a NAVAIR competition for the selection of a contractor to continue development of the TERCOM guidance system. The test route layout was in the Arizona–New Mexico area to permit the competing systems to be flown in by a U.S.A.F. C-141 aircraft. A team of APL staff members, including David Kalbaugh, Joseph L. Luber, and Donald D. A. Gray, supervised the actual testing, reduced the data, and scored the results. The McDonnell Douglas Company met the accuracy requirements for the operational system and was selected as the developer of the new guidance system.

During the mid-to-late 1970s, the Air Force was developing an Air-Launched Cruise Missile (ALCM) with the same general range and accuracy requirements. The Office of the Secretary of Defense directed a commonality study of ALCM and Tomahawk, and APL provided a team to work with the Air Force's Wright Laboratory to pursue the investigation. The designs were found to have a high degree of commonality in guidance and propulsion. As a result, a Joint Cruise Missile Program Office (JCMPO) was established with the Navy designated as the lead service. After the selection of Boeing as the Air Force prime contractor, jurisdiction for the ALCM returned to an Air Force program office. The emphasis on commonality continued in JCMPO with the Air Force Ground-Launched Cruise Missile (GLCM) program. The missile was virtually identical with the nuclear Tomahawk and was carried on a special transporter with associated ground-control equipment. In the mid-1980s, over 400 missiles were deployed in Europe. Besides providing a major capability, they served as a powerful bargaining chip that led to the withdrawal from Europe and subsequent destruction of SS-20's and GLCM systems.

When the JCMPO was formed in late 1977, CAPT Walter M. Locke, who had just been selected for promotion to Rear Admiral, was named as Director. RADM Locke held this office until 1982. During his decade tenure (1972–82) as leader of cruise missile efforts, RADM Locke was a visionary, innovator, and promoter. He advanced the cruise missile cause despite resistance from many entrenched interests. A particularly apt description of RADM Locke's contributions was provided upon his retirement. A plaque from the Boeing Company reads: "He had the vision to see the possibilities of the cruise missile and the courage to bring them about." As Director of the newly formed JCMPO, RADM Locke requested that APL maintain an on-site presence to provide a thread of continuity and an educational service as the office grew from a mere handful of individuals to a staff of more than 300.

Although the Tomahawk missile is a remarkable achievement and can fly long distances autonomously with pinpoint accuracy, it will only do what it is preprogrammed to do. Before launch, the missile is initialized and provided with a detailed mission from the launch point to the target. Every action, including speed changes, course turns, climbs and dives, and navigation updates required to reach the target is included. To accomplish this mission planning and to predict results, a mission planning system was developed in parallel with the missile, ship, and subfire control systems and launchers. The Navy Theater Mission Planning System (TMPS) is installed at two ashore locations under the control of the unified commanders, Commander-in-Chief Pacific and Commander-in-Chief Atlantic. The completed missions are loaded into a Data Transport Device (DTD) in digital format for delivery to the firing platform, and original missions and updates can also be sent through communications links. The TMPS makes extensive use of databases, including digital terrain elevation data, vertical obstructions, point positioning data, photographic images, enemy defense locations and capabilities, and so on. After the mission is planned, preflight predictions of factors such as ground-clobber probability, navigational accuracy, probability of defense penetration, and probability of arrival are computed and provided to the launch platforms and controlling staffs. On board the ship or submarine, the weapons control system plans the overwater trajectory to the first TMPS preplanned waypoint, combines it with the overland mission from the DTD, and loads it into the missile. Figure 4 depicts the Tomahawk land-attack mission, including the Digital Scene Matching Area Correlator (DSMAC) map locations that will be described in a later section. McDonnell Douglas personnel conceived the idea of the TMPS based on their test planning experience and won a competition to develop it. Laboratory personnel led by Robert W. Dougherty played an important role over the years in establishing how the TMPS would employ databases provided by DMA.

Interest in a long-range antiship missile continued as the strategic guidance system was being developed, and widespread concern over the Navy's ability to target the Tomahawk missile led to a new task for APL. The Navy had in hand a prototype system to correlate positions of ships from many sources. Could data from this system be used to target a long-range missile out to hundreds of miles? The Laboratory helped formulate and later participated in Project Outlaw Shark exercises that demonstrated that such targeting was feasible. The validity of the system was shown by simulated launches of antiship Tomahawk missiles in the Mediterranean Sea using a ground station in Naples, a surface ship, a submarine, and support from an APL team. On the basis of test program results, the Navy continued to develop the correlation system and the missile. To support Outlaw Shark, Joseph C. Schissler prepared an Antiship Employment Manual that described the targeting problems in terms of sensor report accuracy and timeliness and missile navigation capabilities. The manual also described for the first time the search patterns that the missile and its seeker could use to find the target. This publication was the first of many APL-prepared documents describing Tomahawk system operation in a form operators can use more easily.

The concepts proven by Outlaw Shark were embedded in the Tomahawk Weapons Control System for surface ships and the Combat Control System for submarines. The antiship function provides a correlated over-the-horizon targeting picture, plans the engagement by selecting appropriate search patterns, and computes probability of success.

In 1978, Joseph L. Luber was appointed Project Engineer for Tomahawk—a position he held for five years.

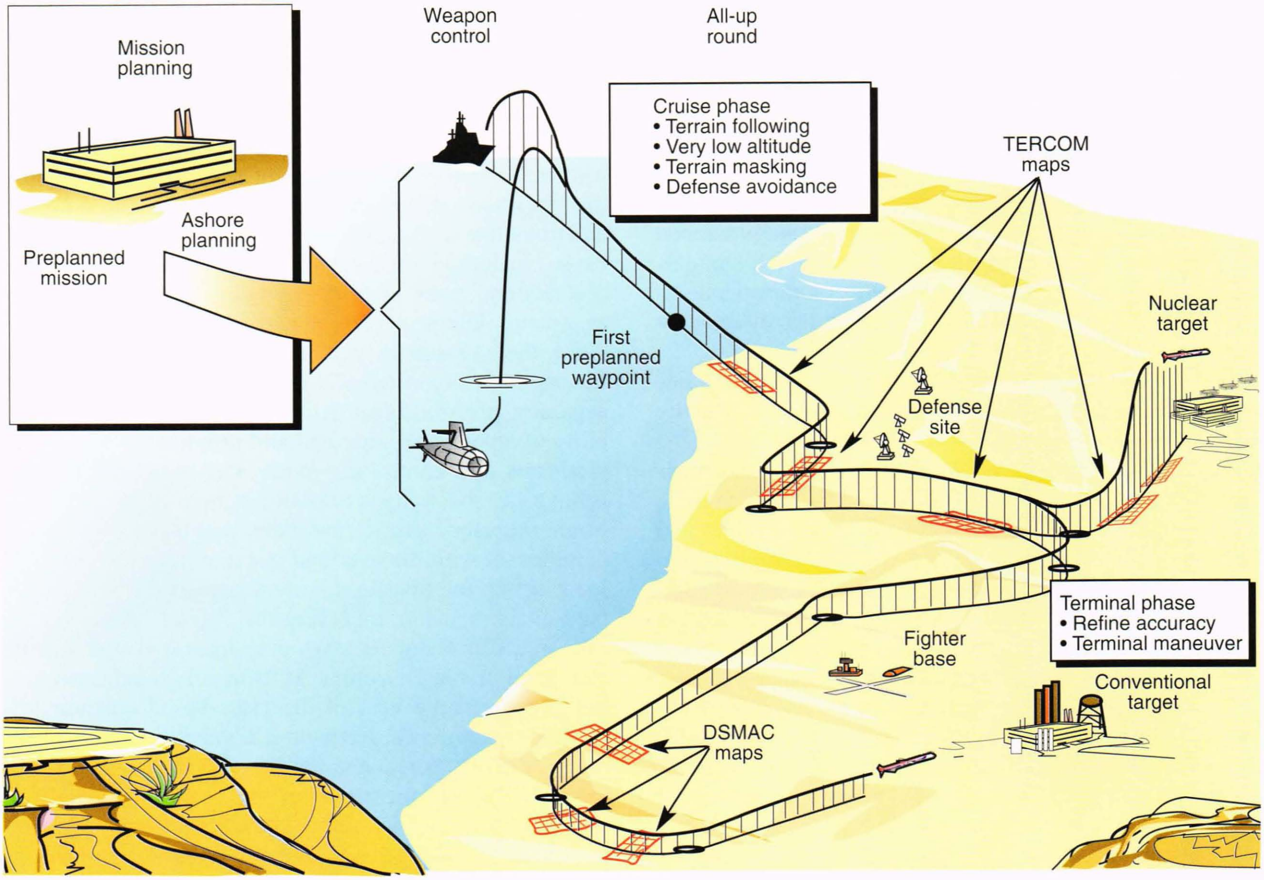

Figure 4. The current Tomahawk Land-Attack Missile operational concept, including the cruise and terminal phases. The overland mission is planned ashore and provided to the firing ships and submarines. The weapons control system plans the overwater trajectory to the first preplanned waypoint and combines it with the overland mission (DSMAC = Digital Scene Matching Area Correlator, TERCOM = Terrain Contour Matching).

Under his leadership, the Tomahawk program at APL expanded significantly, growing fourfold in total funding and increasing its breadth as relationships with new offices at JCMPO were established.

THE 1980s

Basic development of the Tomahawk missile was completed in the early 1980s, when the difficult operational test and evaluation and transition-to-production phases began. In 1982, RADM Stephen J. Hostettler relieved RADM Locke. One of RADM Hostettler's first actions was to modify and strengthen the cruise missile infrastructure. Navy Lead Labs and System Engineering Integration Agents were assigned for both the missile and the weapons system. With his experience in earlier programs (Tartar and Standard Missile) and his familiarity with the Laboratory, RADM Hostettler designated APL as the cruise missile Technical Direction Agent (TDA). The TDA serves as the technical conscience of a program and provides technical advice and expertise to the Navy program manager. Typical TDA tasks include development of requirements, assessment of performance, identification of problems and their solutions, detailed effectiveness analysis, and preparation for the future by developing concepts and conducting engineering prototyping. This new responsibility broadened the APL charter to embrace all elements of the Tomahawk weapons system and greatly increased the scope of the Laboratory's program. With a long record of achievement as a program manager at APL, Marion E. Oliver was assigned as Tomahawk Program Manager. RADM Hostettler formed a small team, including Marion Oliver, that spearheaded efforts to solve problems hampering Tomahawk's transition to production. This team introduced and enforced a new discipline in the program by identifying clear organizational responsibilities, establishing design baselines, firmly controlling changes, and focusing management attention on solving the most pressing difficulties. Over the next four years, the initial problems were solved, and Tomahawk went into production.

One of the major accomplishments during this era was the development of a credible land-attack capability based on a high-explosive warhead. A 1977 flight-test demonstration of an analog optical scene matcher, which was originally developed by the Naval Avionics Facility in Indianapolis, promised an order of magnitude improvement in guidance accuracy. A digital optical scene matcher called the Digital Scene Matching Area Correlator (DSMAC) was later introduced. Similar in many respects to TERCOM, DSMAC uses digitized pictures of the selected area instead of elevation profiles. The concept is shown in Figure 5.

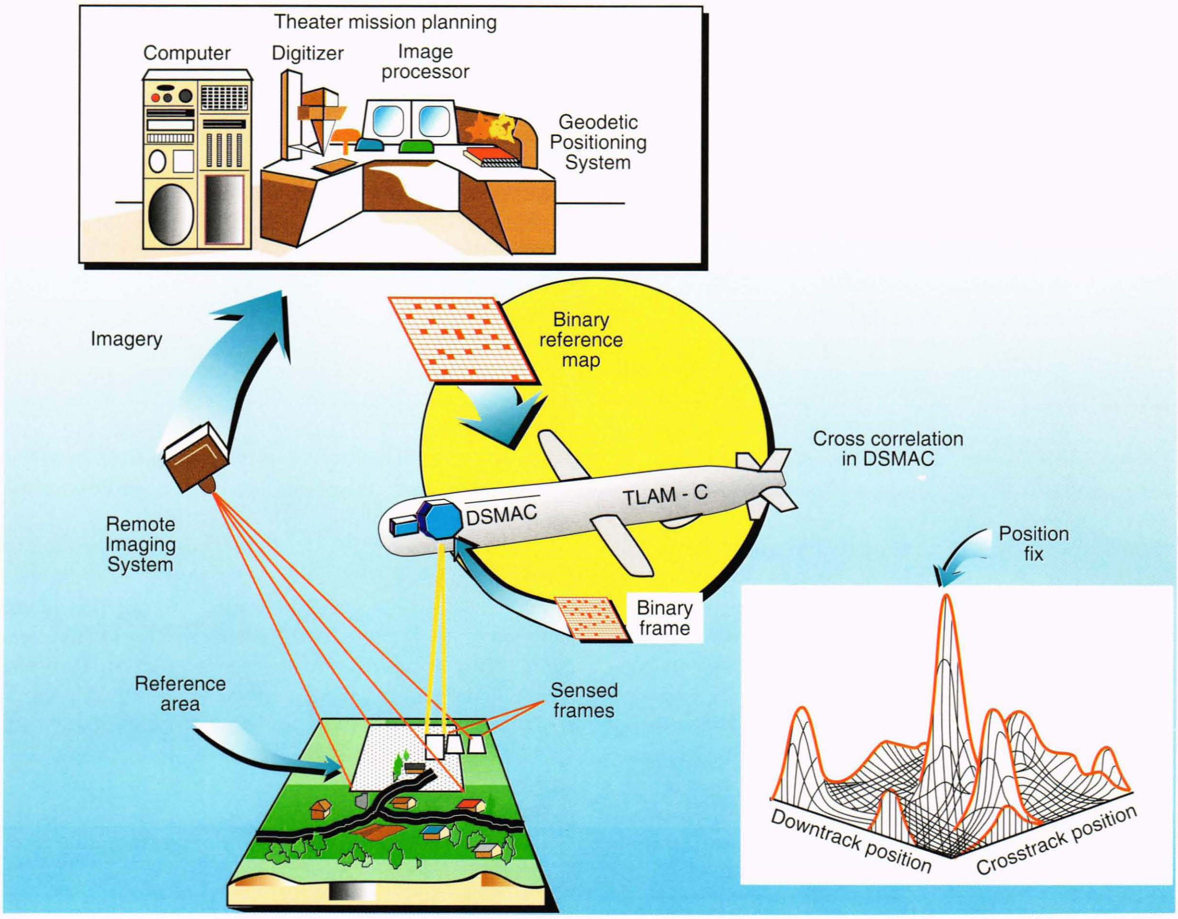

Figure 5. The Digital Scene Matching Area Correlator (DSMAC) operational concept. The prestored binary reference map is compared with the scene sensed by the missile's TV-like sensor, and a precise navigational update is then generated (TLAM = Tomahawk Land-Attack Missile).

The Mission Planning System selects appropriate ground-scene areas for DSMAC maps and, after detailed evaluation and precise location of the scene center, inserts the digitized black and white image into the mission. When the missile is initialized for firing, the mission data, including all the DSMAC maps, are loaded. At the appropriate time in flight, the missile software turns on the onboard DSMAC television camera that takes pictures of the ground. These data are digitized and then compared with the stored image, pixel by pixel. An extremely accurate position update is provided to the guidance set. The first conventional warhead variant carried a unitary 1000-lb warhead and used a combination of TERCOM and DSMAC updates to achieve its extreme accuracy in horizontal attack or programmed warhead detonation modes.

For Tomahawk to be targeted against specific aimpoints, such as buildings and power plants, a terminal dive maneuver is required. The development of the new terminal dive capability was led at APL by John F. Walter. Alan J. Pue and Frederick W. Riedel assisted the contractor, McDonnell Douglas, in defining the terminal maneuver methodology.

As a result of the impressive success of the conventional Tomahawk operational evaluation, VADM Metcalf sent the following message:

> This achievement marks the beginning of full participation in strike warfare by the surface Navy, and will allow our ships to provide critical support to our TACAIR forces in meeting the strike missions of the future. Seldom has a need been better met, a goal more clearly achieved. Well Done.

The Air Force withdrew from the program as GLCM's were removed from Europe. The Tomahawk Cruise Missile Program became a Navy-only program, and the project was moved to NAVAIR. RADM Lawrence E. Blose became the Program Manager and continued the emphasis on fleet introduction and the development of full Tomahawk capability.

The Laboratory formed a Strike and Antisurface Warfare Program Office in 1987 by consolidating efforts in surveillance and targeting, air weapons, and defense suppression with the long-standing Harpoon and Tomahawk projects. The new office reflected APL's focus on warfare areas (Antiair Warfare, Undersea Warfare, etc.) as appropriate definition of organizational mission. Ross R. Hatch was appointed Program Area Manager, replacing Marion Oliver. Joseph L. Luber was Assistant Group Supervisor of the office until 1991, when he retired as Tomahawk's "Gray Eagle," the individual with the longest continuous service to the program.

In 1987, RADM William C. Bowes relieved RADM Blose. Drawing on his attack aviation background, RADM Bowes emphasized overall strike coordination and improvements to increase flexibility and responsiveness. Each element of the total weapons system was reviewed, and complementary improvements were defined. A major upgrade of the Mission Planning System called the Theater Mission Planning Center Upgrade was approved that will dramatically reduce the time to plan individual missions and provide an afloat planning capability for capital ships such as carriers and command ships. One of the keys to this new system was the introduction of a Digital Imagery Work Station (DIWS). A primary feature was an improved performance prediction capability that enabled the planner to select DSMAC scenes of the highest qualty. Robert Dougherty and Geoffrey B. Irani were instrumental in providing technical analysis and algorithms for incorporation in DIWS.

In parallel with the primary system upgrade, a missile Block III program was initiated. During his work on DSMAC II, Irani invented a new concept of scene matching (for which a patent has been allowed) using correlation addition of multiple scenes rather than independent correlation of individual scenes. His DSMAC IIA concept greatly expanded scene availability and simplified mission planning. The Laboratory and the Naval Avionics Center cooperated in the basic design that was implemented by the McDonnell Douglas Missile System Company. A second feature was the incorporation of a Global Position System (GPS) receiver that allowed worldwide navigation updates without the need of TERCOM; thus, mission planning flexibility was increased. Missions with GPS and DSMAC retained the high accuracy achieved by TERCOM and DSMAC. Missions using only GPS were also possible with some degradation in accuracy. The third improvement was time of arrival (TOA) control. In the basic system, the TMPS estimates time of flight that the shooter can use to provide an estimated time of arrival at the target. Several factors, including temperature, wind, and engine variations, can cause changes to this estimate. Both throttle control and changes in flight path length were used to achieve TOA's well within the requirements for coordinated Tomahawk and aircraft strikes. Throughout these upgrades, Michael D. Foust served as the Principal Technical Adviser to the Project Manager.

In the late 1980s, the inventory of Tomahawk's was increasing rapidly, and an appreciation of this new capability swept the fleet. RADM Bowes recognized that, as with most new capabilities, an information offensive was required to assist all levels of the chain of command in understanding the capability and employment of Tomahawk. A key element was improved documentation. Joseph Schissler, assisted by an APL subcontractor, authored an extensive classified Tomahawk Technical Description Document (T^2D^2). This document provides descriptions of the capabilities, limitations, and basic employment concepts for use primarily by staff officers who are responsible for directing Tomahawk operations.

An extensive flight test program using Operational Test Launches was initiated in the late 1980s. More than 200 launches from ships and submarines demonstrated the ability of ship crews and the quality of the hardware. In concert with the Harpoon program, jamming equipment was provided for antiship mission tests. Under the direction of Andres E. Dan, APL played key roles in the comprehensive test program that included setting objectives to ensure test realism, assisting in test planning, and assessing accuracy.

The 1980s brought two major upgrades to Harpoon. In 1985, the missile featured greater range, midcourse waypoints, improved sea skimming, and alternate terminal attack trajectories. The improved sea-skimming mode was based on a "probability of clobber" model developed by Edward P. Cunningham during his years of analysis and testing of cruise missile terrain-following. An improved seeker with digital signal processing and advanced ECM capability entered production in 1989. Its development was based on the results of an experimental program led by APL in 1981 and 1982.

As a result of the loss of an aircraft over Lebanon in 1984, the Navy recognized the need for a long-range standoff precision-guided weapon. To fill this need, the air-launched Standoff Land-Attack Missile (SLAM) was created by removing the radar seeker from Harpoon and substituting the imaging infrared seeker used in the Maverick missile. To provide enhanced midcourse guidance, a GPS receiver was added to provide accurate position data. In addition, the Walleye two-way data link was installed to afford man-in-the-loop operation. Stanley D. Cox provided critical mission planning analysis and assisted in the implementation of the system. Operational evaluation of the SLAM missile commenced in 1989—three and a half years after the initial contract was awarded.

THE 1990s

The beginning of the 1990s found Tomahawk and Harpoon at sea in significant numbers. The fleet had learned how to employ Harpoon and was rapidly learning to use Tomahawk. The surface navy and the submarine force had joined the carriers as members of the strike team. Development programs for improvements in Tomahawk and SLAM were well under way. As we entered the last decade of the century, few realized the changes that would occur.

The decade began with great hopes for peace as a result of the reduction in East–West tensions caused by the changes in the Soviet Union and the unification of Germany. The Iraqi invasion of Kuwait on 2 August 1990 changed this peaceful outlook, however, and put the United States and the United Nations in a very difficult international position. As has happened so often in our history, the Navy was first on the scene and quickly augmented the on-scene forces with Carrier Battle Groups that provided the major deterrent capability until Army and Air Force units arrived.

The Laboratory was extremely active in the Desert Shield preparations for what was to be called Desert Storm. The decision makers recognized that it would be essential to place weapons accurately with minimal collateral damage—especially in the initial strikes. Considerable resistance, however, was presented to using a weapon meeting these requirements that had never been used in combat. The following paragraphs provide highlights of the many activities conducted to increase Tomahawk's credibility.

Priority was given to developing a briefing package that could be used to convince the decision makers of the demonstrated accuracy and reliability of Tomahawk. The Laboratory had been critically involved with the Operational Test Launch program and accuracy analysis for several years, and thus the necessary data were quickly assembled. Given the voluminous data and graphs, the question was how to present the data simply. Since it was World Series time, a baseball field analogy seemed appropriate. The distribution of test program hits was shown about an aimpoint at a pitcher's mound. The presentation was dramatic—especially when coupled with the almost 100% success record in firings during 1989 and 1990. The information was provided to the Joint Chiefs of Staff, and we like to think it played a part in the decision to employ Tomahawk. The baseball chart reportedly showed up in the offices of senior Defense Department officials and at the Central Command Headquarters in Riyadh.

The terrain in the Persian Gulf area made the selection of TERCOM maps difficult, and Dennis Sesak worked closely with DMA and mission planners to solve this problem. He provided modifications to the software that validated TERCOM maps suitable for the operational situation, and acceptable maps were developed for the initial phases of the mission. The DSMAC scenes needed were also a challenge. Questions regarding the required scene stability, shadow effect, and contrast were evaluated with the aid of a software package prepared by James P. Christ. Geoffrey Irani's role in settling several vital DSMAC issues was characterized by RADM Bowes as a key factor in establishing confidence in Tomahawk deployment.

The question of collateral damage was raised repeatedly, since many of the targets of interest lay within urban areas. Civilian casualties and damage to other buildings were to be avoided. Dennis Sesak and Frederick Riedel developed a probabilistic approach that could be used to assess probability of remaining within a safe radius. The approach was used by the staffs in approving Tomahawk targets. Coordinated strikes with F-117 stealth fighters were a key element of Desert Shield planning, and strike planners used the times on target methodologies to determine if adjustments to the mission planning times were required.

A system developer rarely has the opportunity to see the product of his hard work demonstrated for the first time in such a dramatic fashion as did the developers of strike warfare weapons used in Desert Storm. Almost 300 Tomahawk missiles were fired with outstanding results. The shooters included battleships, Aegis cruisers, Spruance destroyers, and attack submarines located in the Persian Gulf, Red Sea, and the Mediterranean. The Cable News Network (CNN) showed the SLAM results vividly. The overall performance of strike weapons launched from ships, submarines, and aircraft was impressive and heralded a new era of strike warfare.

Coincidental with the end of Desert Storm, RADM Bowes was relieved as Program Executive Officer for Cruise Missiles and Unmanned Aerial Vehicles by RADM George F. A. Wagner, who had served as the Tomahawk Surface Ship Program Manager in the mid-1980s. The challenge from Desert Storm was to verbalize the lessons learned and to develop improvement programs to address them. The Tomahawk and Mission Planning Upgrade programs already addressed the needs in many areas. The Applied Physics Laboratory was assigned the lead role in an effort to define a new Baseline Tomahawk that would reflect the experience gained from Desert Storm and take advantage of emerging technologies in the fast-paced warfare field.

CONCLUSION

Over nearly five decades, contributions by APL have assisted significantly in providing the Navy with an unequaled antiship and land-attack capability from surface ships and submarines and have expanded the strike capacity of naval aviation. As demonstrated in combat, power projection from surface ships and submarines complements carrier airpower. This distributed strike capability can only assume even greater importance in the future as force levels are reduced while potential areas of regional conflict multiply.

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THE AUTHORS

ROSS R. HATCH (center) is a 1956 graduate of the U.S. Naval Academy and holds an M.S. in Engineering Electronics from the U.S. Naval Postgraduate School and an M.S. in Financial Management from George Washington University. He is a graduate of the Defense Systems Management College Program Manager's Course. Mr. Hatch joined APL in 1985 after a Naval career that included assignments at sea in destroyers and cruisers, two tours to the Antarctic, and service as Commanding Officer of the USS *Semmes* (DDG-18) and the USS *Belknap* (CG-26). Ashore he was AAW Branch Head in the Office of the CNO, NAVSEA Tartar/Standard Missile Program Manager, Deputy Aegis Program Manager, and Director of Surface Combat Systems, NAVSEA. He is presently the Program Area Manager for Strike and Antisurface Warfare in the Fleet Systems Department and was appointed to the Principal Professional Staff in 1989. Programs under his cognizance include Tomahawk, Harpoon, SLAM, AMRAAM, AAAM, HARM, E-2C, and Space and Wide Area Surveillance Projects. Previous assignments were as the FP-2 Tomahawk Technical Assistant and Tomahawk Program Manager. He is a member of IEEE, ASNE, and the Naval Institute as well as numerous conservation/environmental groups.

JOSEPH L. LUBER (right) is an aeronautical engineer who has spent most of his career managing the development of guidance and control systems for ballistic and cruise missiles in which the Fleet Systems Department and its other organizational predecessors were interested. Among the weapons programs in which he has been involved are Talos, Triton, Typhon, a Landing Force Support Weapon, the Standard Missile, and, more recently, Tomahawk. Mr. Luber joined APL in 1954 and took advantage of the evening education program sponsored by the Laboratory to earn an M.S. in Aeronautical Engineering in 1959. He spent the last nineteen years working exclusively on Tomahawk in various management roles, including Project Engineer for a critical five-year period starting in 1978, when the participation of the Laboratory was expanded fourfold. When Mr. Luber retired early this year, Admiral W. C. Bowes, NAVAIRSYSCOM, presented him with the Grey Eagle award for longest continuous service.

JAMES H. WALKER (left) graduated from Kansas State University in 1942 with a B.S. in mechanical engineering. He served in the U.S. Navy in World War II and joined APL in 1947. He was elected to the Principal Professional Staff in 1953 and assisted in the early design and development of Terrier, Talos, and Tartar surface-to-air missiles. In 1966–67, he served as Chairman of the U.S. Navy's Advanced Point Defense Study Group. Mr. Walker was Assistant Supervisor of the Triton Division and was the first APL Program Manager for the Harpoon and Tomahawk weapon systems. He has been a lecturer in Aerospace Engineering at the University of Maryland and presently teaches a course in system acquisition in the JHU Continuing Professional Programs. Since retiring in 1986, Mr. Walker has served in a consultant capacity on Patriot development and as Study Leader for a National Security Industrial Association report on the feasibility of antiship tactical ballistic missiles.