GEORGE F. EMCH

AIR DEFENSE FOR THE FLEET

Fifty years ago, the Applied Physics Laboratory was established by Johns Hopkins University to carry out the task of developing a proximity fuze for naval antiaircraft artillery shells. The proximity fuze was developed and put in production in an incredibly short time. After that, the Laboratory went on to study the broader problem of air defense for the fleet. This article will outline the role of the Applied Physics Laboratory in the progress in that area during the past fifty years.

ANTIAIRCRAFT GUNS

The basic antiaircraft (AA) gun fire-control problem is to orient the gun barrel at the time of firing such that the target and the projectile occupy the same space at some time during the time of flight of the projectile, based on observation of the flight path of the target and knowledge of the gun ballistics. Because of the unlikelihood of a solid projectile causing significant damage to the target by simple collision, all except the smallest-caliber guns fire shells that explode on contact with the target. Given the wide lethal radius of the explosion of the larger shells, as compared to the diameter of the projectile, the probability of target damage can be greatly improved by causing the shell to detonate when it reaches the vicinity of the target. Until the advent of the radio proximity fuze, detonation was accomplished by exploding the shell after a time delay that was set at the time of firing. Thus one not only had to predict where the target was going, but exactly when it would get there.

The successful development of the radio proximity fuze is discussed elsewhere in this issue, in the article by Berl. Briefly, the proximity fuze (Fig. 1) contains a small, simplistic radar set that detonates the round when it detects the presence of a nearby target.

Although the proximity fuze greatly improved the effectiveness of anti-aircraft artillery (AAA) fire, accurate target tracking and precise computation of the target's future position was still required. The Navy's Mk 37 gun director system, developed in the 1930s, provided a reasonably adequate solution to the AAA problem of the era. However, that massive system could not be fitted into the Navy's thousands of auxiliaries, amphibious ships, and small combatants that relied on the five-inch gun for their organic air defense.

At just about the time of the first combat employment of the proximity fuze (by the cruiser USS *Helena*) in 1943, an APL team developed the Mk 57 gun director (Fig. 2). This handlebar director, operated manually by one man, provided aiming results comparable to the Mk 37 gun director and it was much smaller than the Mk 37, so that it could be widely used on the smaller vessels.

Given the understanding of the fundamental strengths and weaknesses of ballistic gunnery as a defense against

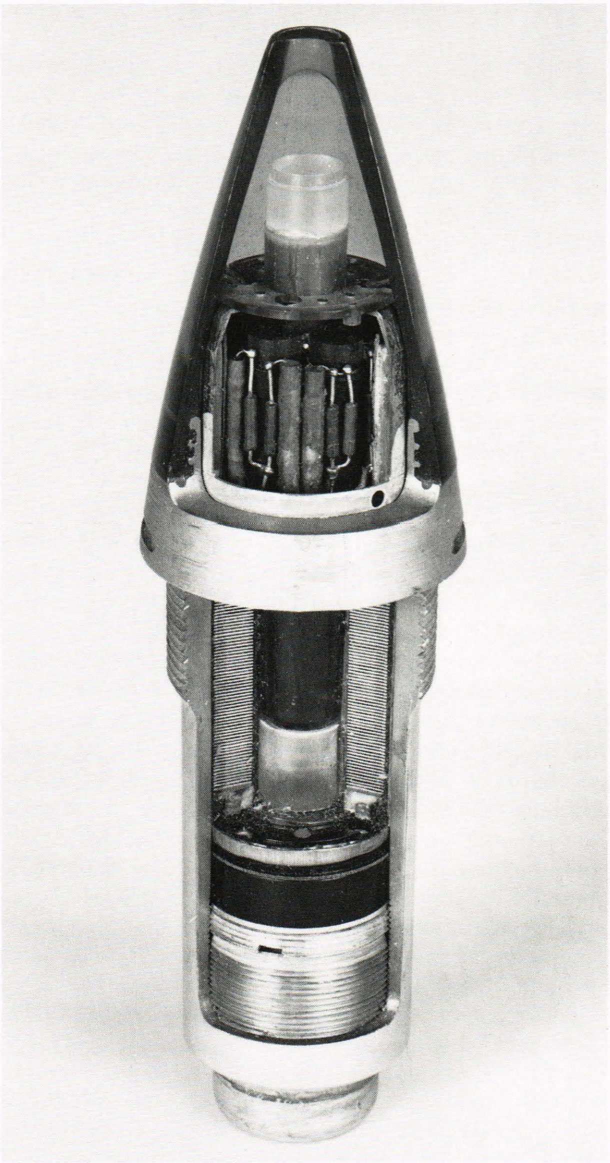


Figure 1. A World War II Mk 45 radio proximity fuze, one of the later Army models.

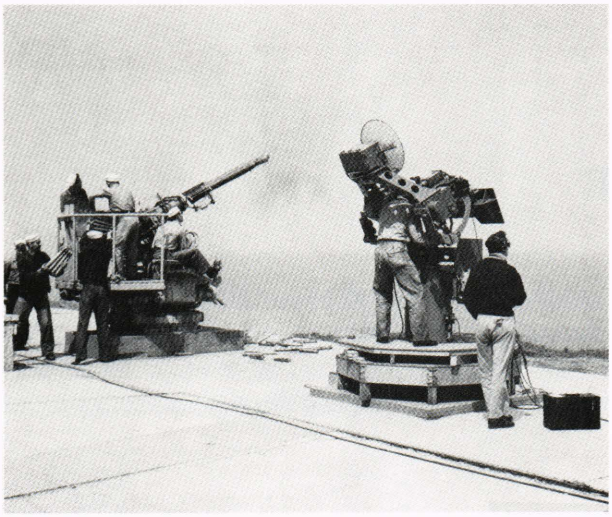


Figure 2. Testing of the APL-designed Mk 57 gun director by a Navy crew at Dam Neck, Virginia.

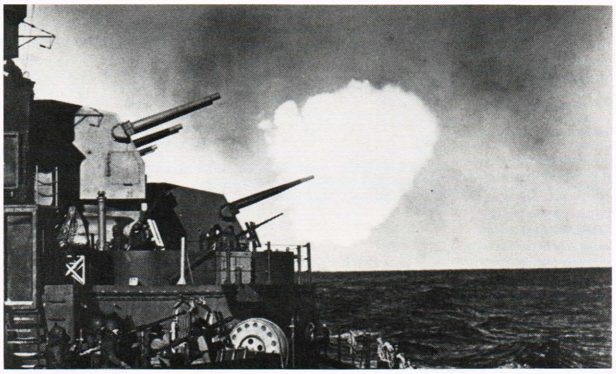


Figure 3. The 5-in./38, 1.1-in., and 20-mm guns that produce the "ring of steel" air defense.

air attack that was gained during the development and service introduction of the proximity fuze, the successful employment of radio-guided bombs by the Germans against ships, coupled with a knowledge of the burgeoning U.S. development efforts to field several models of such ordnance, it was realized that the "ring of steel" provided by AAA guns (Fig. 3) would not be able to adequately cope with the increased launch ranges of these new threats. Further, the limits on projectile muzzle velocity achievable with chemical propellants, coupled with the wide uncertainty of future target position when a projectile could reach the required engagement range, made it clear that a new technical approach was called for—not new guns.

ANTIAIRCRAFT GUIDED MISSILES

The aerial torpedo, long a staple of the science fiction of the time, took a step toward reality when the Navy contracted APL in December 1944 to develop a supersonic jet-propelled guided missile that could destroy air targets at ranges from 10 to 20 nmi. While the proximity fuze program continued at full speed, APL chose the ramjet for propulsion and began work on the detailed design of an air-defense missile and the assembly of the technical specialists and creation of the research facilities needed to support such efforts. The ramjet had been demonstrated only with subsonic flow, so this was indeed an ambitious undertaking. But why was the choice made to use a ramjet for propulsion in a supersonic missile?

Traveling at twice the speed of sound, a missile would take over one minute to reach a target at 20 nmi. If an incoming target were closing with a ship at 480 kt, it would be necessary to fire a missile when the target was at a range of 29 nmi in order to achieve a maximum-range intercept. To minimize both an enemy's ability to successfully employ evasive maneuvers or other countermeasures, and also the time that the missile guidance channel must be occupied in engaging a single target, it is essential that a missile have a significant speed advantage over even the fastest target that it must intercept. With the requirement for long-distance supersonic flight and shipboard constraints on missile size and handling hazards, the ramjet is attractive because it uses oxygen from the atmosphere for combustion, unlike chemical rockets that must carry their oxidizer. With only liquid-fueled rockets available as an alternative at the time, the ramjet was an elegant solution.

Under the leadership of Wilbur Goss, the acquisition of a supersonic ramjet thus became a principal element of the Bumblebee missile program, involving the creation of a working theory of ramjet operation and the assembly of facilities for engine construction, laboratories for ground testing, and ranges for flight tests. Within six months, powered flight of a supersonic ramjet over a distance of five miles was demonstrated, and the continuing evolution of expert knowledge and unique experimental facilities which have kept APL in the forefront of supersonic (less than Mach 3) and, later, hypersonic (greater than Mach 3) propulsion commenced.

In parallel with the propulsion effort, conceptual design and development of the missile's guidance and control systems proceeded. In 1945, APL selected radar beam-riding as the means for guiding the missile. In this technique, a radar continuously tracks the target while transmitting a collimated guidance beam that is modulated in a manner that enables the missile to sense its location relative the center of the beam. This form of command guidance was well suited for shipboard use in that only one radar-director structure was required per target engagement channel, and a succession of missiles could be fired up the beam to increase the certainty of target destruction.

As in the earlier proximity fuze development, APL marshalled the technical resources of academia, industry, and the military establishment to form a team that, by 1947, was engaged in an active experimental flight program. Ramjet-propulsion test vehicles and solid rocket-propelled steering test vehicles (STV) were being flight tested at the new Naval Ordnance Test Station at Inyokern, California (Fig. 4), and design of a ramjet-propelled guidance and control test vehicle (XPM) was in progress. Using an approach more recently called "build a little, test a little," wind-tunnel test data were used with electromechanical flight simulators such as the APL yaw sim-

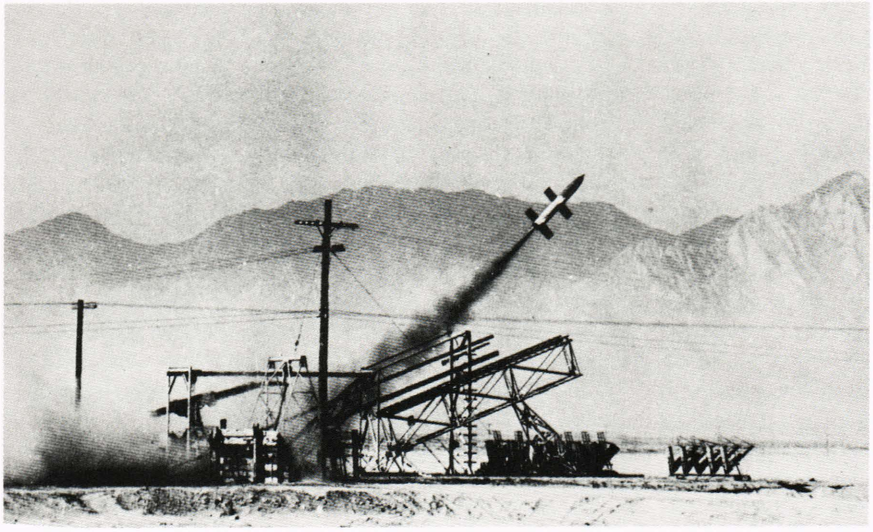


Figure 4. A control test vehicle firing at the Naval Ordnance Test Station, Inyokern, California, on 22 October 1946.

ulator (Fig. 5) to predict the flight performance of the STV. From comparison of the observed performance with the predicted performance, the theory could be refined and designs could be adjusted.

With the realization by the U.S. that the expectation of universal peace and good fellowship held in 1945 was not shared by the Soviet socialists and their converts, the Navy felt an urgent need for an intermediate-range (15- to 20-nmi range) AA missile. Although significant progress was being made on the ramjet missile, it was clear that it could not be ready for service use in the required time. Henry Porter of APL suggested that the STV-3 test vehicle could be rapidly turned into a tactical missile that would meet the need. In early 1948, the Navy decided to proceed with that course of action and named APL as Technical Director of the development. Richard Kershner was appointed to lead the APL effort on the missile called Terrier (a name selected by Kershner and Ralph Gibson, Director of APL), and with the outbreak of the Korean "police action" later that year, APL went to an extended work week to get on with the job. In addition to the fun of creating a missile that worked well, it was also necessary to work with industry to provide a design that would perform reliably and could be built economically in large numbers. The Navy undertook the responsibility for the design and production of the missile launchers, magazines, fire-control directors, computers, and weapon-direction equipment, and APL was tasked to provide missile information to the Navy bureaus and their contractors who were engaged in this effort.

At the start of the 1950s, the threat of nuclear bombs and jet aircraft was almost universally accepted and the fact that they were technological capabilities of potential enemies of the U.S. was recognized. Although the nuclear weapons tests at Eniwetok had shown that a fleet could survive, with some loss, atomic bomb explosions, it was clear that survival of surface forces required an ability to destroy aircraft at long ranges and high altitudes. Aerodynamicists at APL had chafed at the restriction that the use of variable-deflection wings (wing control) placed on the maneuverability of the missile, particularly at high altitudes. Wing control was a prudent choice for the initial missile because of inherent aerodynamic stability and the perceived need to maintain low body angles of attack for ramjet propulsion.

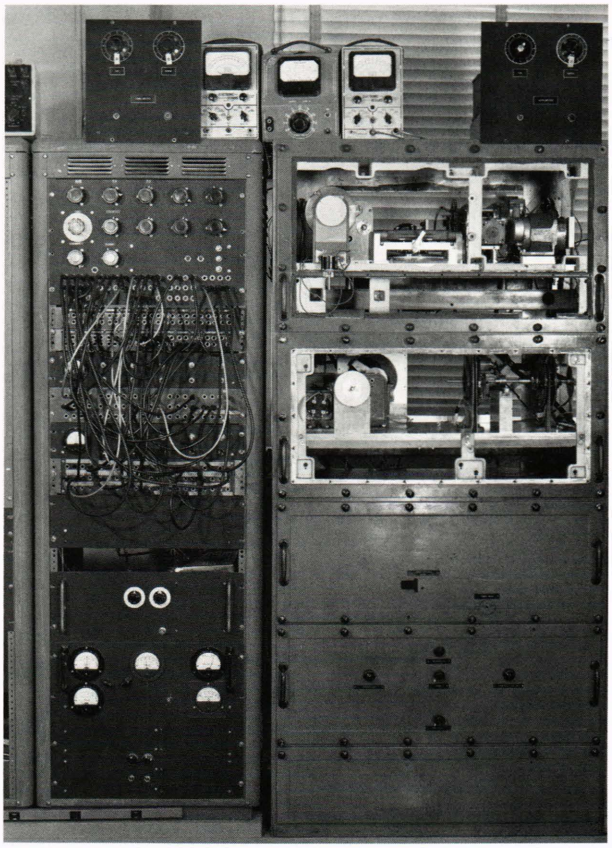


Figure 5. The APL yaw simulator.

Tail control, as is used in conventional airplanes, alters the body angle with respect to the line of flight and uses the area of the missile body to provide lift, which is badly needed at the edge of the atmosphere. In 1948, under the direction of Al Eaton, wind-tunnel and composite-design studies were initiated to define a tail-controlled rocket-powered missile configuration (Fig. 6) that could intercept high-speed targets at very high altitudes. These studies paved the way for the introduction of tail control in Terrier and Tartar missiles at the end of the 1950s[1] and its continued use in their successors, the family of Standard Missiles.

Early in the Bumblebee program, it was recognized that beam-riding guidance could not ensure the small miss distances that are required by chemical explosives at intercept ranges beyond 10 to 20 nmi. Thus one of the early articles of faith was that a means for the missile to sense the location of the target and home on it could be successfully developed. Given the technology and experience of the time, semiactive radio-frequency homing seemed to be the best alternative. Infrared guidance, as used in the Sidewinder missile (then under development), is limited in range by the atmosphere, and in 1947 supporting technology was sparse. Active RF homing (putting a tracking radar in the missile) was, because of missile size constraints, impossible at the time, and even today supports only limited practical performance in all environments. In semiactive RF homing, the target is illuminated by RF energy from the launch platform and the missile senses and homes on the energy reflected by the target.

An essential element of any RF homing missile is the antenna, which gathers the RF and senses the direction of its source. The normal approach, then as now, is to use a parabolic reflector (a "dish") or a lens to concentrate the energy and, through mechanical articulation, to determine the direction of the source. This approach, while eminently suitable for rocket-propelled missiles, was impossible for ramjets because of their requirement for a large, unrestricted nose orifice. To meet these disparate physical requirements, APL drew on the resources of its colleagues and adapted a dish homer developed for the Sparrow missile by the Raytheon Company for use in the rocket-propelled missiles, and the ideas of O. J. Balzer (University of Texas) and L. J. Chu (MIT) were applied to provide an interferometer homer for Talos.

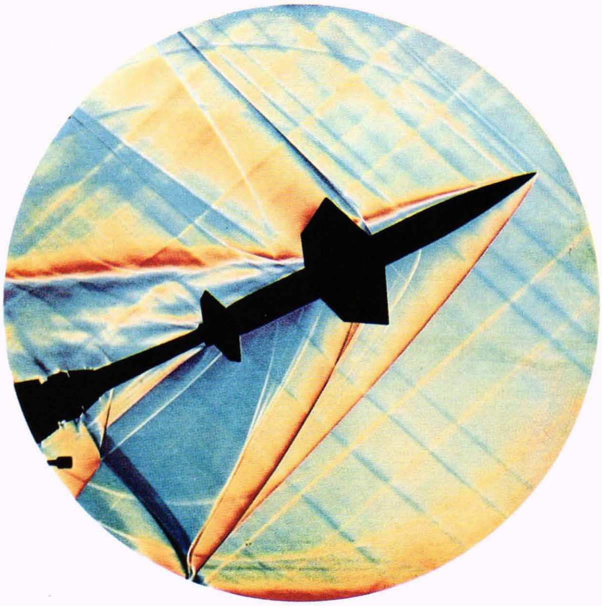


Figure 6. Early wind-tunnel test of a pre-Terrier II STV-4 test vehicle (with tail control) shows the supersonic airflow patterns that occur during steering maneuvers.

The interferometer, with its four symmetrically placed stub antennas on the nose of the missile, has the advantage of relatively broad frequency bandwidth but lacks the RF directivity of the dish. Homing on the target is achieved by minimizing the rate of change in angle, which, as any capable mariner knows, results in collision. (These characteristics were later exploited in an antiradiation version of Talos, which was reported to have "shut down" North Vietnamese air-defense radars for a week.)

The directivity of the dish antenna homer for the rocket-propelled missiles provides resistance to electronic countermeasures, and both types of homers support a passive mode of operation in which the missile homes on the source of jamming at its operating frequency. Thus, accommodating the inherent differences between the rocket- and ramjet-propelled missiles, APL provided a broad spectrum of missile capabilities needed by the fleet—a long-range (greater than 50 nmi) ramjet missile for use against medium- to high-altitude bombers, and effective intermediate-range rocket-propelled missiles for use at all altitudes.

In 1950, the U.S. government responded to the world situation by deciding to have one thousand Terrier missiles built in order to prove that they could be mass produced. The Convair Corporation, which had constructed the STV-3 test vehicles and which was the Product Engineer for Terrier, was contracted to build a missile plant in Pomona, California, and to produce the missiles. Convair experienced difficulty in turning out reliable missiles at the required production rate, despite help from APL missile experts.

The basic problem soon became evident to Richard Kershner and Alexander Kossiakoff: the missiles were being built by the same methods used for assembling airplanes. That is, an airframe was fabricated and then the other parts were fastened on, and wiring and plumbing were connected. Kershner and Kossiakov suggested that a missile, like a round of ammunition, should be designed so that it could be assembled from a set of functional modules (sections), with each section specified such that it could be built and tested independently and would therefore be interchangeable with other sections of the same type. The Laboratory proposed a program to demonstrate the principle; APL would provide the production design, the several sections would be built by selected contractors, and Convair would assemble them to produce finished missiles, which would then be flight tested to prove the design. The Navy accepted the proposal and tasked APL to build and test ten missiles that were designated as Terrier IB. The task was successfully completed on schedule and within cost estimates, with eight of the nine missiles fired scoring complete successes. With the predicated advantages of sectional design fully realized, many of the concepts and features of the IB design were ultimately incorporated by the production contractor into the Terrier I.

Later, incorporating the results of the tail-control studies mentioned earlier, Terrier missile design was radically altered, with still more effective sectionalization. Initial production of those tail-controlled beam-rider and homing designs began in 1959. Al Eaton provided technical direction of the program. The program was especially notable because, in terms of cost, about 85% of the component parts of the beam-rider round and the homing round were directly interchangeable. Leaders in the production design process were Walter Foley, Ben Amsler, and Fred Goldbach.

Under the lash of the growing threat posed by the Soviets, the U.S. Congress authorized the construction of a new class of guided-missile destroyers armed with Terrier to join the two Terrier heavy cruisers that were still undergoing conversion. Conversion of three light cruisers to carry the Talos missile was also approved. Recognizing in 1951 that the missiles under development were not suitable for installation in many of the smaller ships that needed a better air-defense capability, a team headed by George Carlton was set up to address the problem. In the team's study report, issued in 1952, the team proposed a small, boosted, tail-controlled missile and recommended a study to define the shipboard system.

In March 1954, Thomas Sheppard headed a Small-Ship Guided-Missile study group to extend the earlier work, and in July of that year the group outlined a proposal for a compact system that embodied the basic concepts of what was to be the Tartar system. This proposal was forwarded to the Navy and, after consideration of it and other proposals, it was favorably endorsed. Following the submission of a refined program plan based more directly on the use of Terrier technology, the Tartar program was born in early 1955.

The Tartar missile concept took full advantage of ongoing Terrier developments featuring a sectionalized-design, tail-controlled aerodynamic configuration that used many of the same components as Terrier. Two unique new features were the use of a integral "dual-thrust" rocket motor, which eliminated the need for a separable booster rocket section, and folding, self-erecting tail-control surfaces. This latter feature, the invention of Sverre Kongelbeck of APL, replaced the rigid control surfaces used by Terrier and Talos that had to be manually attached to the missile just before it was run out on the launcher for firing. That earlier design required a large missilehouse and a handling crew, and added several seconds to the time required to bring a missile and its booster from the magazine and position it on the launcher, ready to fire.

Those new missile features enabled the design of an integrated missile magazine and launcher structure that would accommodate over forty missiles and which could be fitted in a space about the same size as that occupied by a twin 5-in./38 gun mount and its magazine. By replacing one of the twin 5-in. mounts with the launcher, modifying the associated fire control radar to add a target-illumination beam, and adding a missile fire-control computer and weapon-direction equipment, a "gun" destroyer could be converted to use AA guided missiles.

Always alert to the potential of new technological developments for forwarding its work, APL acquired one of the first Reeves electronic analog computers (REACs) built by the Reeves Instrument Co. for the Navy under Project Cyclone. The new computer was put in service by two Ph.D. summer students, Ernest Gray and James Follin. The versatile instrument was quickly expanded to replace the awkward electromechanical simulators used in the initial Bumblebee development. In support of the Bumblebee Dynamics Group (BBD), first under George Carlton and later under James Follin, those electronic analog differential analyzers were used extensively in the development of the guidance and control systems of all of the APL missiles of that era (Fig. 7).

Perhaps one of the most significant contributions of BBD was the development of the Kalman–Bucy theory of nonlinear filtering. Kalman filters are now a staple element of modern control systems. About a year after the arrival of the first REAC, one of the first commercially available digital computers, an IBM 604, was acquired to augment the arduous labors of people doing manual calculation using pencil, paper, and Marchant (or similar mechanical, electric-motor-driven) calculators.

The year 1955, eleven years after Johns Hopkins University accepted the contract for APL to develop an AA guided missile, found APL as the leader of a consortium of academic and industrial organizations engaged in the development and production of guided missiles that had achieved an impressive list of "firsts" covering all aspects of missiles, from propulsion to warheads. During this period, a foundation of design concepts was established, on which the continuing successful evolution of the Standard Missile family is based. The first AA guided missile ship, the USS *Boston*, was in active service, with several additional ships under construction. Although the primary focus of APL's efforts during this time was missiles, assigned responsibilities to provide "missile infor-

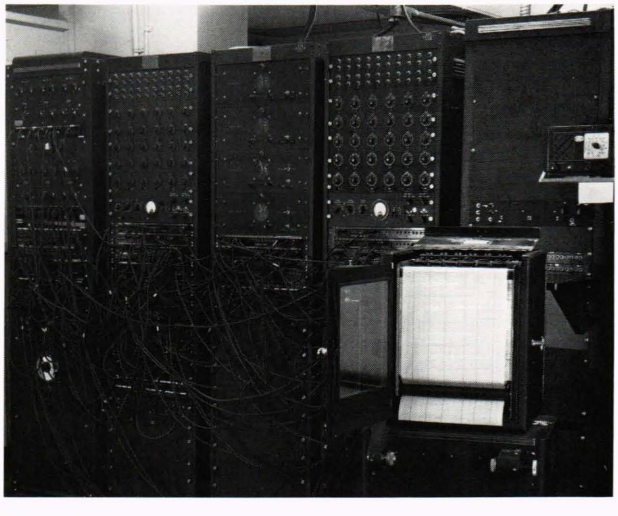


Figure 7. One of the early Reeves electronic analog computers at APL's first location, 8621 Georgia Avenue, Silver Spring, Maryland.

mation" to the naval activities and their contractors who were engaged in the production and integration of the shipboard missile system spurred APL interest to also contribute to development in this important area.

During this period, APL made the transition from a temporary wartime activity of the University to a permanent University Division. In keeping with this new status, a permanent site was acquired in Howard County, and APL's "New Building" (the portion of Building 1 that is now the east and south wings) was dedicated on 16 October 1954. A new propulsion research facility (now the Avery Propulsion Laboratory) was designed to replace the Forest Grove facility, which was the subject of complaints from the horde of recently arrived neighbors.

GUIDED MISSILE BATTERY

With Terrier in active service at sea, the activities of more APL staff members gradually shifted from the missile round and its components to the ship's missile battery. Although most of this activity, and indeed most firing tests, took place on *terra firma*, the small number of staff members involved in shipboard tests was also augmented, as the tempo of missile firings increased to provide training as well as development. Systems groups were set up for Terrier (led by Robert Morton) and Talos (led by Al Ennis) to carry out APL's responsibilities of ensuring compatibility between the missile and the shipboard equipment.

Although many of the problems were clearly of an engineering nature (such as collimation of the fire-control radar tracking and guidance beams), a few (such as the difficulty experienced by the beam-rider missile in intercepting low-flying targets, a continuing nemesis of surface ships) were more fundamental. When the beam was directed close to the surface, reflections from the water caused the missile to receive erroneous signals. An engineer in the Terrier Group, William Vann, devised a scheme to modulate the power of the beam such that the power at the bottom of the beam was reduced when it was near the sea, thereby greatly ameliorating the problem.

With the rapid proliferation of Terrier ships and the need for frequent checks of beam collimation, APL developed special instrumentation, under the leadership of Tom Sheppard and Ralph Robinson, that was installed with collimation towers at naval bases throughout the world. In 1952, a Central Laboratory Assessment Division, under Charles Meyer, had been set up with the role of establishing a perspective of the tactical conditions in which AA guided missiles would be employed and to specify how missiles would have to perform under those conditions. As evidenced by the wartime development, production, and deployment of optical proximity fuzes (which used a photoelectric cell to detect passage of the shell from sunlight into the shadow of a target aircraft), under the direction of Kirk Dahlstrom, APL has long held a great respect of the potential effects of hostile electronic countermeasures (ECM). Thus the Division was particularly sensitive to this aspect of the tactical environment and was a strong force in APL's participation in the DoD Weapons Systems Evaluation Group's tests of U.S. air-defense capabilities.

In response to the evident threat that ECM posed to missile systems, the Technical Director of the Laboratory, Alexander Kossiakoff, initiated the construction of an ECM battle simulator to aid in the evaluation of the vulnerability of Navy AA combat systems and the identification of effective counter-countermeasures. Although members of the fire-control community, with their new-found resource of tests in operational missile ships, spurned its use, it was an essential tool for the weapon-direction system work. In cooperation with APL psychologists Jack Gebhardt and Randel Haines and under the supervision of the author, the simulator was used to run a series of experiments during 1961 and 1962 to determine whether naval commanders would accept computer-generated recommendations for air defense of a force (Fig. 8). The responses of a number of U.S. Navy commanders to a week of simulated air battles in ECM environments strongly suggested that computer recommendations were positively received.[2]

By the start of 1962, the problems of the fleet with the new missile batteries had reached the point that the APL-developed missiles were tagged as the "terrible Ts" and the Director of the Laboratory, Ralph Gibson, recommended to the Secretary of the Navy that a comprehensive program be undertaken to characterize and develop solutions to the problems.

In response, the Navy appointed Rear Admiral Eli Reich to form and head a Surface Missiles Systems Project. As a former commander of the USS *Canberra* (the second Terrier ship), and an experienced ordnance officer, this World War II submarine hero was well prepared for the assignment. Following a series of inquires, APL was requested to assume technical direction of the missile fire-control and weapon-direction equipment (the missile battery, less the launchers). To address this new responsibility, APL established a Fleet Systems Division headed by Thomas Sheppard (assisted by Milt Moon and Roy Larson), who reported to Wilbur Goss, Assistant Director for Technical Evaluation. A companion Missile Systems Division, headed by Al Eaton, was established to continue the missile-development efforts.

This Fleet Systems undertaking differed from previous APL efforts in that the subjects to be addressed already existed in the form of tangible equipment, much of it already installed in ships. Applying the customary academic approach of analysis and equipment, personnel of the new Division rapidly deployed to the industrial contractors supplying the equipment and to the ships in which the equipment was installed. It quickly became apparent that while the Navy had treated surface missiles systems as a straightforward extension of gunnery systems, the rigid operational discipline of frequent battery alignment and daily transmission checks had been discarded. The mistaken assumption was that, since the missile guides itself to the target, attention to those important details was unnecessary.

Working with its long-time industrial contractor, Vitro Laboratories, APL developed road maps of the systems (one-function diagrams) alignment procedures, and daily system operability tests to be performed by the ships. System Compatibility and Requirements Specifications

Figure 8. Electronic countermeasures simulator computer-assisted command experiment. Battle umpire station computers (top). The commander in the combat information center (bottom).

were developed under the leadership of Ned Wharton and Clyde Walker for each ship system and Development Assist Tests were conducted for each new ship class. For these tests, APL provided the test plan, test conductor, special technical assistance (including expert help from the contractors producing the equipments), special instrumentation to measure and record performance, data analysis, and a final test report.

Those ship test activities, which involved about ten major events a year, fully occupied the time of the premier APL test conductor, Edward Murdock; his chief assistant, Hugh Wilson; and their colleagues. It became apparent to APL and the Navy that continuing development of the fire-control systems would be expedited by the establishment of a development-support facility at APL that was equipped with production equipment. In 1964, a complete Terrier Mk 76 fire-control system commenced operation (in Building 40), and in 1967 portions of a Tartar radar were added to the facility. This experimental resource greatly facilitated creation of a host of improvements for Terrier as well as supporting a continuing succession of APL experiments dealing with a wide range of fleet air-defense developments.

Recognizing that many such fleet-support activities were not appropriate for APL on a sustained basis, the Navy, with APL assistance, set about the formation of a permanent government activity—the Naval Ship Missile Systems Engineering Station at Port Hueneme, California, in 1963. Similarly, in view of the importance of ECM to the fleet, APL arranged for the use of an airplane specially configured for ECM testing of the Bell Laboratory–developed Nike missile system. That B-47, which was operated by Douglas Aircraft, was used in a jamming test demonstration off the Virginia Capes against the USS *Yarnell* (which was performed at 2:00 a.m. to avoid interference with television broadcasting).

Following the sobering success of that educational endeavor, the Navy placed Douglas under contract to provide the nucleus of the Fleet Electronic Warfare Support Evaluation Group. That group, through their indefatigable efforts, has flown ECM missions in support of fleet training and development tests throughout much of the world on a nearly continuous basis. Without the availability of those services, the high capability of the fleet's people and equipment to contend with ECM would not exist.

While the new shipboard-equipment responsibilities drew much attention, APL's missile developers continued to make great progress during this period. The Terrier II (beam-rider) replaced the first design in 1958 and the

Terrier II (homer) was put in service in 1960. Talos 6B missiles joined the fleet in 1955 with the improved Talos 6C1 and the first Tartar missiles arriving in 1959.

While the majority of APL activities on behalf of the fleet were concerned with the evolving development of AA missiles and the operation of the ship's missile batteries that employed them (from target assignment to kill evaluation), a small cadre was assigned to become knowledgeable concerning the ship's search radars and combat information center (CIC), which (among many other things, including anti-submarine warfare) functions to initially detect aircraft, evaluate their threat, and assign hostile aircraft to a missile battery for engagement.

The development and procurement of the missiles and the shipboard equipment in the ship's missile battery was the responsibility of the Bureau of Ordnance (the Navy sponsor of APL's work) while the Bureau of Ships was responsible for the search radars, the displays, and the plotting boards used in the CIC.

Although the search radars had undergone significant improvements in power and reliability since World War II, there was no difference in the demanding human-operator process of visual target-detection and -tracking on radar scopes, and verbal reporting and manual plotting of the situation display in the CIC. Based on the judgment of the senior CIC officer (the evaluator), targets were verbally assigned to weapons for engagement. Operators of the weapon-direction equipment observed displays of the search-radar video and tracked the assigned targets. The weapon-direction equipment (WDE) developed by Bell Laboratories for Terrier and Tartar incorporated rate-aided tracking facilities that provided a reasonably accurate estimate of the target's current location based on the operator's input of the periodic radar indication of position. This search radar-derived target track was electrically transmitted (designated) to a fire-control director that automatically mechanically scanned its 1.5° radar beam around the designated target position. If the current altitude of the target had been observed on the height-finding (three-dimensional) radar and correctly entered by the WDE operator, the fire-control operator would usually see the target "blip" after about fifteen seconds of acquisition search and put the radar into automatic track. If, however, height information was not available, an extended search would be executed which, if successful, would usually require thirty seconds or more to acquire the target.

It quickly became apparent that even in the best radar environments, this operator-intensive sequence ate up too much time (typically two minutes from initial detection to missile fire), and frequent overflights of undetected test aircraft underscored its inherent fallibility.

By the mid-1960s, the U.S. Navy had over fifty ships armed with 3T (Terrier, Talos, and Tartar) missiles, with more new construction and conversions under way. Although the intensive efforts of the get-well program were succeeding in providing a respectable operating capability, it was clear that systematic upgrade and improvement were needed to meet the imminent air threat. The Navy, with strong APL participation, had established the framework for this in July 1963, when Rear Admiral Eli Reich established a Surface Missile System Technical Planning Group under Captain Robert Irvine. This group, comprised of Navy, APL, and industry representatives, laid out a detailed plan of action to identify and correct the current problems and to guide future development through the 1960s. In addition to outlining efforts for counter-countermeasures improvement, the plan provided for conceptual studies of a new-generation AA guided-missile weapon system.

MISSILE SYSTEMS

Experience with the early guided-missile ships with their systems created by "integrating" individually developed equipments, coupled with the results of Assessment Division evaluations of the current and expected air threat to the fleet, led APL to conduct conceptual studies directed at defining a complete new AA missile system in the late 1950s. The results of those studies and the significant technical advances that stemmed from them are chronicled in the article on the Typhon missile system by Gussow and Prettyman elsewhere in this issue. That revolutionary program—to develop a system using a digital computer-controlled, fixed phased-array radar to automatically search the complete volume around the ship, to detect and track all targets in that volume, and to control a number of missiles simultaneously to counter mass raids—had a profound effect on the technical evolution of U.S. air defense.

As an integral part of the development, two new missile designs were to be created. A long-range ramjet-powered missile (Fig. 9) to destroy standoff jammers and massed bombers would be directed to the target based on radar tracking of the target and, near intercept, by measurements of radar reflections received by the missile and transmitted to the ship (track-via-missile [TVM] guidance). An intermediate-range missile, to counter low-flyers and penetrators, was to be an extension of Improved Tartar.

Under the fiscal constraints resulting from the expanded social programs in the early 1960s and the need to fund the unexpected 3T Improvement Program, the Navy can-

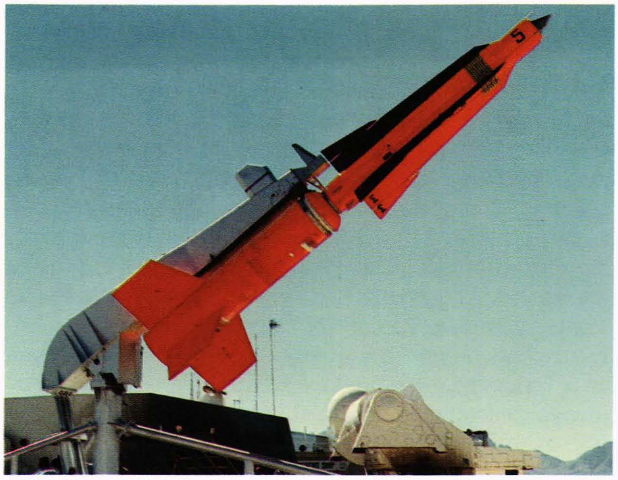


Figure 9. Prototype of the long-range Typhon missile, being prepared for flight at the USS *Desert Ship* at White Sands Missile Range, New Mexico.

celed construction of the Typhon ship and the new missiles. Before this action was taken, however, the TVM guidance system for the long-range missile had been designed and demonstrated. (Track-via-missile guidance is used in the Army's Patriot missile system.)

To economically meet the continuing need for Terrier and Tartar missile upgrades, and building on the results of the APL insistence on the standardization of missile section design to permit direct interchangeability between the two missiles, the Navy consolidated the effort as the Standard Missile Program. The Terrier was designated as Standard Missile (ER) (extended range) and Tartar as Standard Missile (MR) (medium range). Al Eaton initially served as the APL program leader, and was later succeeded by Ray Ely.

During this period, in addition to progressively implementing incremental design changes to improve tactical performance, emphasis was placed on engineering the design such that shipboard testing and adjustment of missiles would be no longer required. Successful achievement of this "wooden round" concept, facilitated by the evolution of solid-state electronics, entailed a sustained effort by the missile-design community and drew on many specialties. For example, the early designs used high-pressure hydraulic systems to actuate the control surfaces, but later development of electric motor-driven actuators simplified the construction of the missile and eliminated the problems associated with hydraulic fluid.

The Bureau of Ships, exploiting the availability of digital computers, addressed the need for modernizing the World War II CIC design still being built into new ships, and put into development the Naval Tactical Data System (NTDS). That system provided the search-radar detectors and trackers with rate-aided tracking facilities and command (the evaluator) a console on which were displayed the current positions and velocity vectors of all aircraft, ships, and submarines being tracked by sensor operators. The computer provided an estimate of the relative threat posed by each track, and controls were provided for assignment and designation of tracks to weapons. Digital data-communication links were implemented to enable ships and aircraft to automatically interchange track information and to enable force commanders to digitally transmit tactical commands.

The NTDS was initially installed in the aircraft carrier USS *Oriskany*, and the Terrier destroyers USS *King* and USS *Mahan*. As funds permitted, it was installed in all carriers, cruisers, the later Tartar frigates, and a number of other ships and aircraft. Today, in updated form, NTDS serves as the core tactical-command support equipment in U.S. surface forces.

The Laboratory's involvement in the initial development of NTDS was primarily that of an interested observer. Advice was requested, however, concerning the logic that should be used for threat evaluation and weapon assignment (TEWA). Alec Radcliff of the Assessment Division developed the fundamental logic for those operations, which was succinctly stated as "nearest, least engaged." This doctrine continues to the foundation of Navy TEWA.

Unfortunate casualties of this electronic progress were the large vertical plotting boards that, by sailor-actuated colored grease pencils, showed the current and past positions (track) of aircraft, numeric indications of altitude and designation, and their identities. Although NTDS console controls permit the track (a series of dots) height and other particulars of a target to be shown, the console display equipment could not present the comprehensive information that had served World War II commanders so well.

In the area of search radar, the Bureau of Ships also undertook bold initiatives. Development of a new frequency-scanned, stacked-beam, three-dimensional (3-D) radar that used digital computation for data stabilization, the AN/SPS-48, was successfully completed to provide an alternative to the less-capable single-beam AN/SPS-39 that was then installed in most missile cruisers and destroyers. An even more ambitious undertaking was the development of an electronic-scanned-array radar suite for large ships comprised of the AN/SPS-32 (UHF) 2-D radar and the AN/SPS-33 (S-band) 3-D radar. This suite was installed in the carrier USS *Enterprise* and the Talos/Terrier cruiser USS *Long Beach*.

Efforts by APL on search radar for the fleet during this period include participation in SPS-48 development tests to determine its suitability for weapons direction. The major APL effort concentrated on the development of an understanding of the effects of ECM and natural clutter on radar target detection and devising means to help radar operators perform their demanding task. Tens of thousand of radar-screen photographs (one per antenna rotation) made at sea during development tests and exercises were laboriously studied to identify aircraft blips and to reconstruct the aircraft tracks for comparison with the performance of the radar operators.

That process was greatly facilitated by the application of magnetic-tape recording technology by Ralph Robinson, Donald Bucholtz, and Richard Pickering to provide continuous recordings of the radar-display outputs. These recordings could be replayed, on demand, using standard radar displays. These radar video recorders (RAVIR) (Fig. 10) provided an essential resource for subsequent radar developments, instrumentation of weapon system tests and fleet exercises, as well as serving as stimulators for a series of radar-operator training programs. (They were limited for combat system team training, however, in that we never did find a way to delete targets that were "shot down" from the radar video).

With the advent of low-flying antiship missiles (ASM) such as the Soviet's Styx, the importance of earlier initiatives to improve missile low-altitude capability, search-radar detection acuity, and designation accuracy became more evident. Although the extensive naval operations then in progress off Indochina (Vietnam) met only infrequent air opposition, with a few ships receiving bomb damage and a number of hostile aircraft destroyed by 3T missiles, the possible threat of Soviet-supplied anti-ship missiles was a matter of concern. (Perhaps more significant were the two still largely ignored incidents in which allied aircraft inadvertently launched anti-radiation missiles [ARM] that totally incapacitated the radars on one U.S. and one Australian guided-missile ship).

In 1967, APL participated in the first fleet studies directed at determining fleet capabilities to counter land-

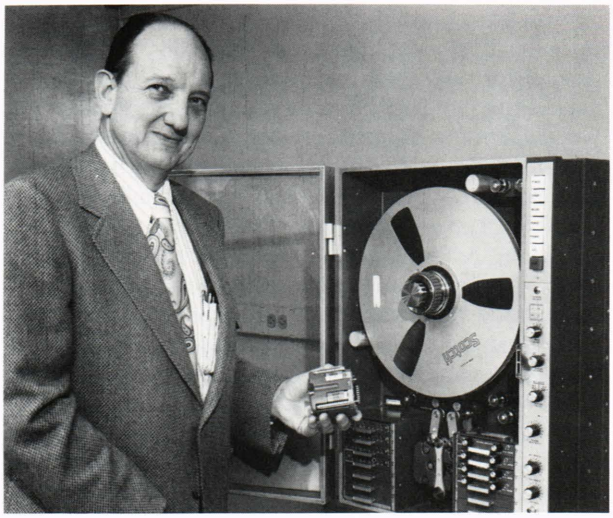


Figure 10. Ralph Robinson with the RAVIR radar video recording system used to record and play back search radar video.

launched anti-ship missiles. In the operational phase of this study, the first unalerted firing of a missile in a ship exercise demonstrated that a Tartar missile could destroy a drone simulating a Styx. Because of the radar-horizon limitation on the range at which low-flying missiles can be detected, it is essential that the target by promptly detected and designated to weapons if the missiles are to have an opportunity to do their work.

As a part of the Antiship Missile Defense Project organization that the Navy set up to meet this threat, APL reviewed the chain of events that normally transpired between target detection and missile firing, and identified shortcuts that could be taken, based on perception of the threat situation. This threat-responsive weapon-control philosophy (originally formulated by Commander Charles Hager and the author) was used to define "quick-reaction" modes of operation for the 3T missile ships. For the few ships equipped with NTDS, implementation of these modes entailed only computer program changes, while *ad hoc* ancillary annunciator systems were provided for the rest.

The remainder of the fleet, however, still suffered from the lack of AA defense capability, which was the reason for the Tartar Program. Terrier missile batteries had been installed in three aircraft carriers but were removed because of "incompatibility" with carrier operations and for reasons of economy. Thus the new aircraft carriers relied on their air wings for defense and the remainder of the surface forces had only the same (or less) AA gun firepower that it had at the end of World War II.

The concept of employing the Sparrow air-to-air missile for ship defense (Seasparrow), which had been proposed as an alternative to Tartar in 1955, was embraced, and a Basic Point-Defense Missile System using a handlebar radar director and a box launcher holding eight of the 12-ft-long air-to-air missiles was put in production (Fig. 11). As a result of this effort, several APL members suffered from *mal de mer* at APL while participating in tests on a rolling, pitching platform devised by Jeff Floyd to demonstrate that the handlebar director could be used to track targets successfully under shipboard conditions. The Navy also initiated development of an automatic radar-directed 20-mm Gatling-gun system (Phalanx), and an APL-proposed concept for a passive dual-mode (RF/IR), short-range homing missile (the rolling airframe missile) was pursued.[3] Over the life of these three point-defense programs, APL has, when requested, provided technical assistance to the extent that resources permitted, and is currently involved in all three.

During the summer of 1968, APL hosted a second Navy SMS Technical Planning Group (TPG II), which was convened to update and extend the plans developed in 1963 in the light of the significant developments that had occurred. The group recommended development of an Advanced Surface Missile System, as is discussed in the following section, as well as laying out detailed plans for the 3T systems, including the incorporation of the principles of threat-responsive weapon control, replacement of the analog fire-control computers with digital computers, and development of Standard Missile designs for Terrier and Tartar, which employed command midcourse guidance.

ANTIAIRCRAFT COMBAT SYSTEMS

With the close-out of the Typhon Program in 1963, the Chief of Naval Operations expressed the need for an advanced surface missile system (ASMS) for installation in new cruisers and destroyers. In response to this need, the

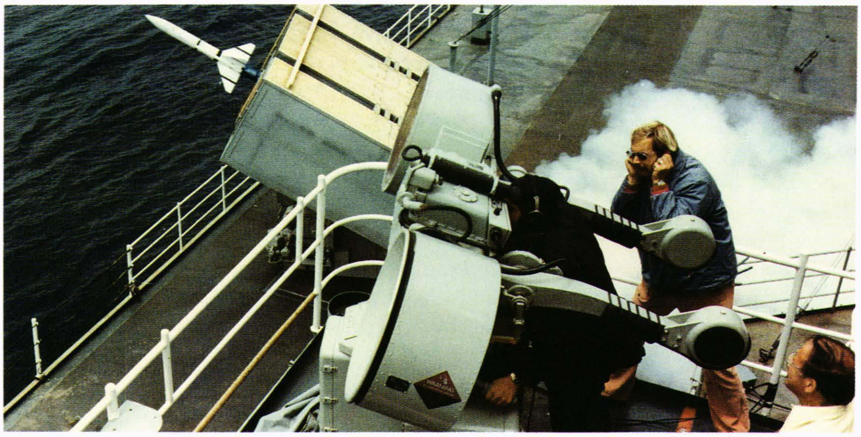


Figure 11. Test firing of the Seasparrow missile system.

Secretary of the Navy chartered an ASMS study group administered by the Bureau of Weapons (BUWEPS) and comprised of representatives from the Navy, Navy laboratories, industry, and APL. By 1965, that group outlined a design concept for a fully integrated missile system centered around a fixed phased-array radar.[4] This concept incorporated, in part, ideas developed in studies by seven industrial teams that were set up by BUWEPS in 1963.

Although the Navy favorably endorsed the concept, development was deferred pending the results of an investigation of the possible use of the Mobile Field Army Air Defense System (Patriot) by the Navy. During 1965, BUWEPS tasked APL to initiate experiments and analysis directed at minimizing the technical risk and validating design concepts of the ASMS and its major components. The principal work performed was the development at APL of the Advanced Multifunction Array Radar (AMFAR). That experimental radar (Fig. 12), the immediate predecessor of the Aegis AN/SPY-1, demonstrated that the concept of pulse-by-pulse control by a digital computer of a radar using crossed-field amplifiers for high-power transmission and a fixed phased-array antenna that used garnet phase-shifters for beam steering was sound and that the radar was highly capable.[5]

The original concept of the ASMS envisioned a new-design missile that used command midcourse and RF semiactive terminal homing guidance. The SMS Technical Planning Group II (1968) determined that the desired new characteristics could be obtained by incorporating upgrade modifications to the Standard Missile (MR) design. In 1969, the decision was made to use the Standard Missile 2 (MR-Aegis) for the system. The salient differences between that missile and those preceding it is that it carries an inertial reference unit and a missile–radar data link; using those facilities, the missile can be guided to the immediate vicinity of the target by acceleration commands based on the precision track of the missile and the target by the SPY-1 radar. One of the significant APL contributions to that development was the evaluation of the missile uplink receiver using AMFAR under conditions where the transmitted waveform was distorted by natural or manmade (ECM) environments.[6] An optimized algorithm that ameliorated those affects on uplink reception was devised and was incorporated into the missile production.

Following clearance by the Department of Defense, the Navy decided to proceed with the development of ASMS (now called Aegis[7]) and to competitively select an industrial contractor to effect the development. In late 1969, a contract for the Aegis Mk 7 Engineering Development Model (EDM) was awarded to the RCA Missile and Surface Radar Division in Moorestown, New Jersey. Continuing to act in its role as technical advisor, APL participated in the critical design review for the system in the spring of 1973 and observed the performance of the newly completed EDM at Moorestown in November 1973 during two days of aircraft-tracking tests. The EDM was installed in the USS *Norton Sound*, and in May 1974 two drone aircraft were automatically detected, engaged, and destroyed. APL staff members closely followed sys-

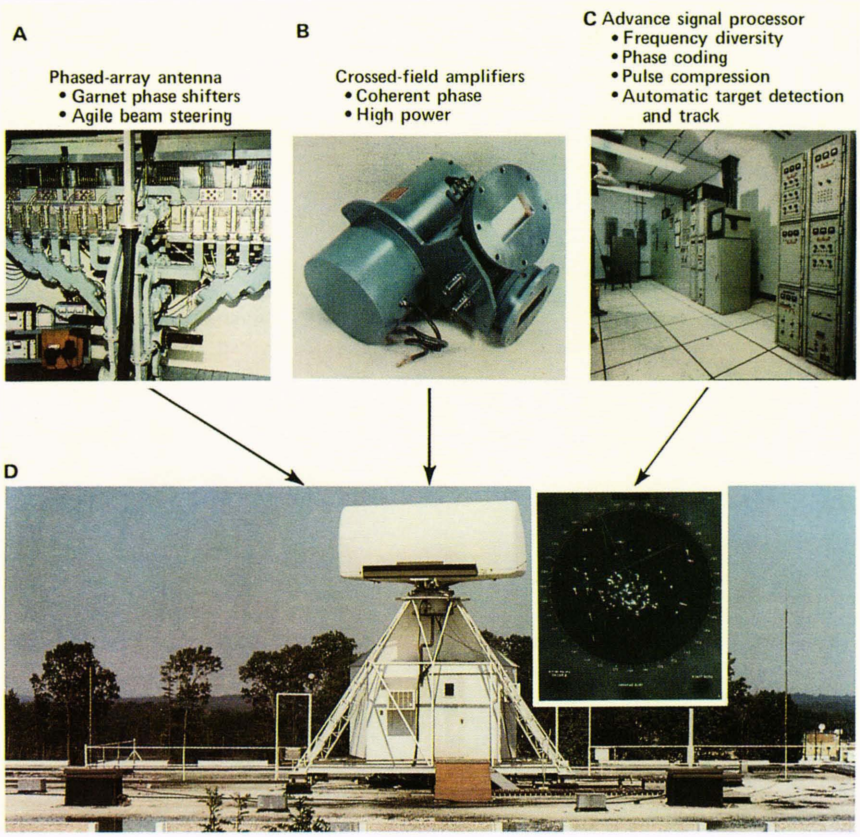


Figure 12. The APL-developed Advanced Multifunction Array Radar (AMFAR). **A.** The antenna array-phasing networks. **B.** A crossed-field amplifier. **C.** The advanced signal processor. **D.** Exterior view of AMFAR.

tem testing and, using the AMFAR and other facilities at APL, suggested a number of improvements, particularly with respect to SPY-1 performance in natural clutter.

The Navy determined that Aegis should be the central equipment of a new class of ships—the strike cruiser. The Laboratory assisted in that initiative by providing analytic assessments of the expected combat capabilities of that proposed class. The Congress, preoccupied with social programs, was unimpressed. An effort was then made to fit the system in a new series of guided-missile cruisers, but it was decided to arm them with Tartar. Finally, in 1977, facing world reality, Congress authorized construction an Aegis destroyer (DDG-47) using the basic hull design of the DD-963 class of ASW destroyers. This ship, now a cruiser (CG-47) was christened the USS *Ticonderoga* in May 1981 as the lead ship of a class of twenty-seven. Thus, eighteen years after CNO expressed the need, Aegis initial operational capability was attained.

Meanwhile, APL had not neglected its responsibilities to the existing guided-missile fleet. The early search-radar investigations by APL conclusively demonstrated that the World War II approach of using humans to visually detect and track target signal returns on cathode-ray tubes was totally inadequate. Under the indefatigable leadership of Alexander Kossiakoff (APL Technical Director, later Director, and now Chief Scientist), work went forward on the development of automatic detection and tracking for the (rotating) search radars of the guided-missile ships.

Using an adaptive-threshold radar video processor (invented by Kossiakoff and Jim Austin) that acts to suppress clutter returns while showing targets visible above the clutter (Fig. 13), in conjunction with the small digital computers then becoming available commercially, a small-ship automatic detection and tracking system was demonstrated by APL. Some of the skepticism exhibited toward that effort was squelched when the Navy accepted three APL-built units of an automatic height tracker for the Mk 8 weapon-direction equipment installed in the USS *Belknap* and the USS *Daniels* (Fig. 14). This ORDALT (ordnance alteration) kit automatically measured the height of all targets under rate-aided track by the WDE using the AN/SPS-48 radar video. This Fleet Systems initiative, led by the author and aided by Steven Tsakos, Russell Phillippi, and many others, received essential assistance from the Space Department, particularly in "hardening" the Honeywell computer so it could survive at sea.

Work continued on automatic detection and tracking (ADT) and in 1970 an experimental system working with the AN/SPS-48 radar at Mare Island, California, was successfully demonstrated. Radar video (RAVIR) tapes recorded in the Gulf of Tonkin during a mass U.S. air raid on North Vietnam exhibited significant degradation of the ship's radar from the ECM employed by the U.S. aircraft against the North. Also, tapes were collected during a major fleet exercise (ROPEVAL 1-70) in late 1969. Tapes from those two sources were used at APL to provide radar inputs to the experimental system in order to demonstrate the vastly superior performance of the system compared to that achieved by humans. Analysis of the results of ROPEVAL 1-70, reported by Richard Hunt and the author, clearly showed the weakness of dependence on human radar operators. In that exercise, the Blue Force, expecting an attack from the south, was overflown by unopposed heavy strikes from the north despite visibility of the raiders in the radar video.

The experimental "proofs" of the need for search-radar automation were widely shown to Navy audiences, and official visitors to APL were treated to demonstrations of the system operating from RAVIR tapes. Under the sponsorship of the Bureau of Weapons, APL assembled an experimental ADT system (SYS-1), which was tested at sea in the USS *Somers* in 1973. That system could operate with either the ship's 3-D radar (SPS-48) or 2-D radar (SPS-49) and could automatically detect and track all targets visible to the radar, while displaying few false tracks. The high track accuracy resulted in target-designation-to-acquisition times that averaged ten seconds.

Laboratory studies of fleet radar recordings clearly showed the complementary characteristics of the lower-

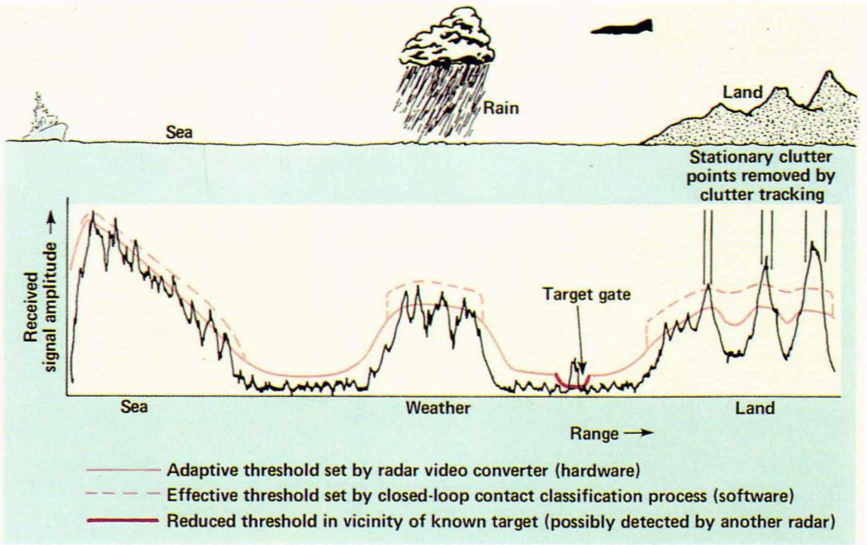


Figure 13. Adaptive threshold video processing is used to remove clutter from radar returns.

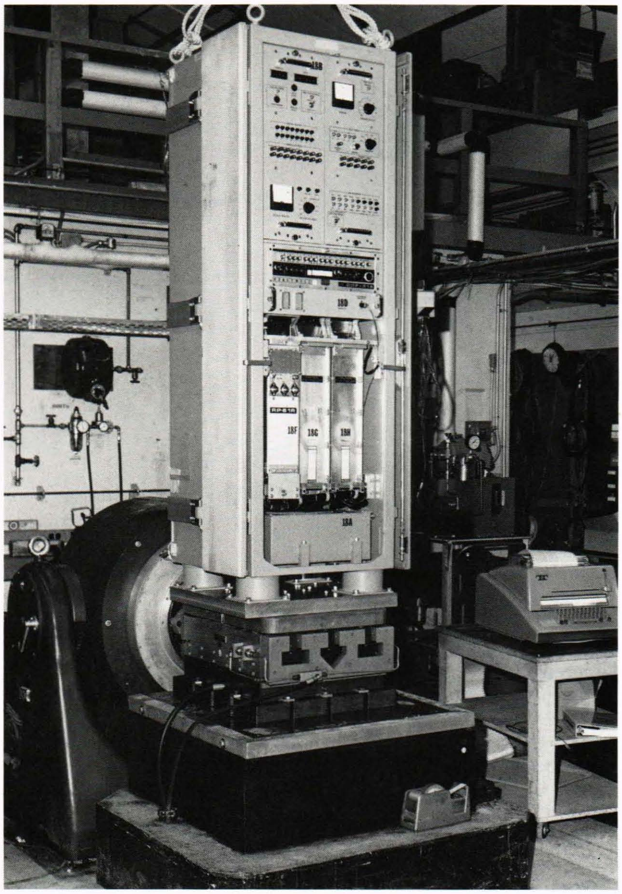


Figure 14. Environmental testing of automatic height tracker for use with AN/SPS-48 radar.

frequency 2-D radar and the S-band 3-D radars that were installed in all 3T ships. The lower-frequency 2-D radars, while much less affected by weather, suffer from systematic gaps in elevation coverage (fades) caused by reflection of the large vertical beam from the water. On the other hand, the pencil-beam, S-band, 3-D radars are seriously affected by weather clutter, but their elevation coverage is minimally affected by surface reflection. Thus, an ADT system that simultaneously used the inputs from both types of radars would clearly be superior.

Alexander Kossiakoff instigated the development of computer algorithms that effectively combined the disparate outputs of the two types of radars to form a single track picture. Using RAVIR tapes as inputs, an experimental integrated automatic detection and tracking (IADT) system was developed at APL and the powerful synergistic gains were confirmed. Targets were detected earlier with better track continuity. Given target range and bearing from the 2-D radar, the sensitivity of the 3-D radar detector can be increased in the small volume holding the target, providing height data sooner. In ECM environments, both radars must be jammed at the same time to deny target detection. Based on the results of the *Somers* tests and the IADT work, the Navy decided in 1975 to make the AN/SYS-1 IADT a part of the DDG-15 class (Tartar) modernization program. An APL-developed AN/SYS-1 IADT system successfully passed extensive operational tests in the USS *Towers* during 1978.[8]

The 1969 recommendation (of the Navy's Surface Missile Systems Technical Planning Group II) that the new Aegis design Standard Missile (SM-2) with midcourse guidance should also be adapted for Terrier and Tartar was a significant milestone in the technical evolution of the 2T (Terrier and Tartar) systems.[9] In principle, midcourse guidance offered increased firepower. Unlike home-all-the way guidance, which ties up one of the ship's (two or four) fire-control radars throughout the missile engagement, the missile can be commanded to fly a maximum–lift/drag trajectory, which nearly doubles the effective range, and fire-control radar illumination is needed only for a relatively short homing phase. The result is that a succession of missiles can be fired at a number of targets in the same vicinity, with one fire-control radar servicing each target as its missile comes up the pipeline.

The problem was to devise practical means within the 2T systems context to develop the midcourse guidance commands and to communicate them to the missile (functions of SPY-1 in Aegis). It was determined that the SPS-48 search radar with its fixed-threshold automatic target detection could normally provide track data adequate to support the decision to fire, initial guidance, and target designation to fire control. The SPS-48, however, could not be expected to track the missile, and the quality of target tracking would not support the Aegis command technique.

It was decided to use an aided inertial system, in which the missile flies toward a point that is set in just before firing and then, if the target changes direction or speed after the missile is fired, a subsequent series of points would be transmitted to the missile over the uplink (Fig. 15). The fire-control radar illuminator was modified to provide coded uplink transmissions to multiple missiles and a communication tracking set (the AN/SYR-1) was developed to receive information downlinked by the missile, to permit the ship to monitor flight progress. Equipment modifications to implement this new capability were developed under the leadership of Marion Oliver. A system development model was assembled at the APL (Building 40) test site and was then taken to sea in 1976 for a development assist test in the USS *Wainwright*. Final operational testing of a production system was completed in the USS *Mahan* in 1978.

By the mid-1970s, projections of the capabilities of Soviet-bloc bombers armed with high-altitude air-to-surface missiles led to their identification as a serious threat to surface naval forces. The Naval Sea Systems Command (an amalgamation of BUSHIPS [the Bureau of Ships] and BUWEPS) directed that a study be performed to determine the capabilities of the Terrier and Tartar (2T) ships against that threat, and to develop a plan to achieve increases in 2T effectiveness needed to meet the threat until the time that the Aegis cruisers became operational. The Laboratory provided the technical leadership of the study group, which examined the threat and characterized it, assessed the capabilities of the 2T systems using the SM-2 Block I missile to defeat the threat, and identified system and missile modifications that would provide the level of performance desired. The recommended system

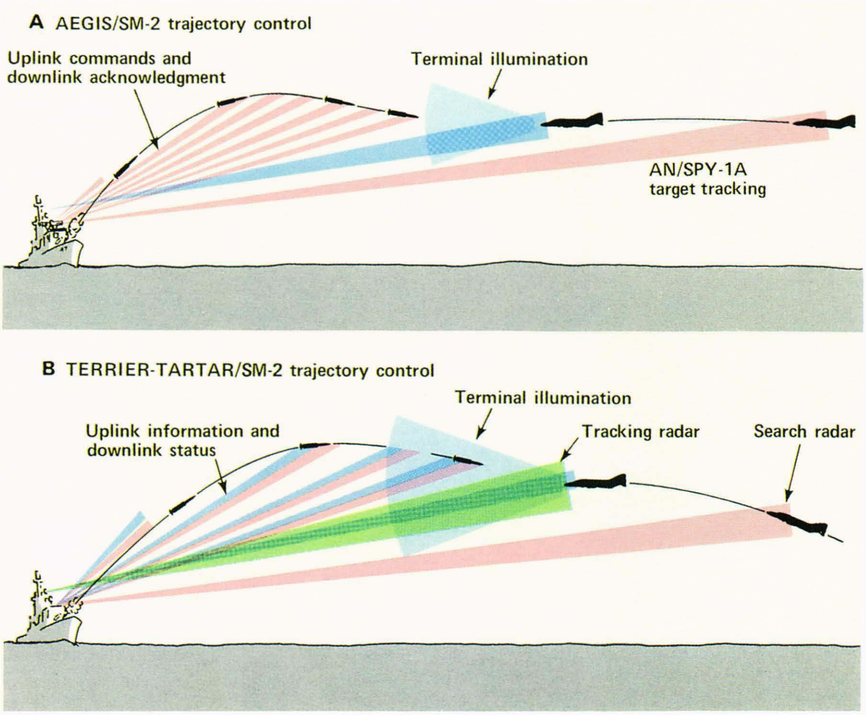


Figure 15. Missilie guidance techniques. **A.** Aegis/SM-2 trajectory control. **B.** Terrier–Tartar/SM-2 trajectory control.

changes involved creation of a new detection subsystem and supporting changes to the command and control subsystem and engagement subsystem that had been developed for use with SM-2 Block 1. Major changes to the missile in the areas of propulsion, signal processing, and the warhead were called for.

In 1976, a New Threat Upgrade (NTU) Program to develop those modifications was implemented by the Navy.[10] As the Navy's Technical Direction Agent for this program, APL coordinated the development of the Terrier system modifications and the improved missile, designated SM-2 Block 2 (ER). Under the leadership of Marion Oliver, James Schneider, and Terry Betzer, an engineering development model (EDM) of the new system was assembled at APL for land-based testing in 1981. The detection subsystem, made up of improved versions of the SPS-48 and SPS-49 radars and a new IADT (AN/SYS-2), and the command and control subsystem effected by a new configuration of NTDS, was installed in Building 11 and the engagement subsystem and a missile simulator in Building 40 (Fig. 16). Within the limitations imposed by the land location, the system, including the new highly integrated detection subsystem, was tested with both real and simulated aircraft in various natural and ECM environments.

The EDM was then installed in the USS *Mahan* for development and operational testing. Following successful completion of those tests, the system was placed in production, with the first Terrier installation accepted in the USS *Biddle* in 1988 and in the first Tartar ship, the USS *Scott*, in 1990. With twenty Terrier and ten Tartar ships planned to be upgraded, the 2T ships will be highly capable companions for the Aegis cruisers and destroyers.

One of the products of the intensive examination of missile-system operation conducted in the mid-1960s in pursuit of reduced reaction time and increased firepower was the vision of a vertical-launching system to replace the pointable, trainable launcher with its relatively long cycle time. The advent of SM-2 with its inertial reference unit made vertical launching feasible from a missile standpoint. In 1977, the Navy embarked on a vertical launching system development program, with Martin Marietta as the prime industrial contractor. The Laboratory played a key role in this program as weapon-system and missile-integration adviser, critical reviewer of the launcher design, and in firing tests of the system on land and at sea (Fig. 17). That APL effort was managed by Russell Phillippi for the system and Richard Constantine for the missile.

A developmental system first launched an SM-2 at White Sands Missile Range in 1981 and from the USS *Norton Sound* in 1982. The production system, which handles Standard, Tomahawk, and proposed ASW missiles, was first installed in the USS *Bunker Hill* and will be fitted in all follow-on Aegis cruisers, the *Arleigh Burke* class of Aegis destroyers, and selected ships of the DD-963 class.

Although the scope of APL developmental activities in anti-air warfare over the past two decades expanded to encompass complete combat systems, early responsibilities to keep the Navy in the forefront of AA missile technology were not neglected. Building on the SM-2 developments briefly mentioned above, APL, in concert with the Naval Weapons Center, China Lake, and the Naval Surface Weapons Center, Dahlgren, in 1984 defined and implemented a program to enhance missile capabilities against very-low-flying targets. The efficacy of this low-altitude improvement program, SM-2 Block III, was demonstrated in test firings at the end of the full-scale engineering development phase.

In recognition of the need to extend the reach of the Aegis fleet, the Navy is developing the SM-2 Block IV

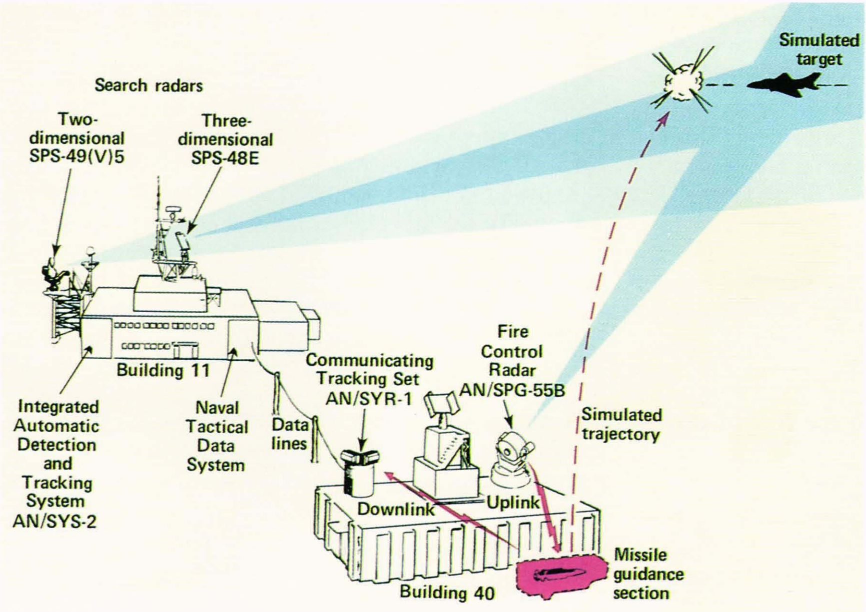


Figure 16. Land-based test site at APL for the Terrier New Threat Upgrade System.

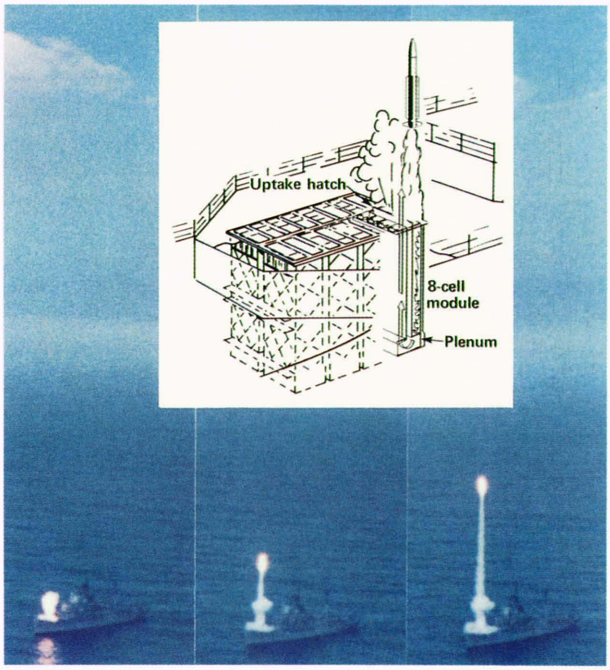


Figure 17. Test firing of a Standard Missile from the vertical launching system on the USS *Norton Sound.*

(Aegis ER) missile. Taking advantage of the relaxation of constraints on length afforded by the vertical launcher, this two-stage rocket-propelled hypersonic missile addresses the need to wage the outer air battle as well as to provide area defense. The Laboratory is continuing to provide technical leadership of this major development, which has progressed to the flight test stage of engineering development. In view of the progress that has been made in IR technology in recent years, and the significant capability that IR guidance could add to missile homing (particularly in ECM environments), APL, as the Navy's Technical Direction Agent, has conducted a High-Performance IR Seeker Program with industry. Products of this program are being considered for application in the SM-2 Block IV development and in the Navy's Homing Improvement Program, which is directed at both Seasparrow and Standard Missile, Block III.

BATTLE GROUP ANTIAIR WAR COORDINATION

Analytic assessment efforts at APL that were directed at evaluating the effectiveness of guided-missile weapons systems to counter the evolving air threat looked not only at the capabilities of a single ship against attack by various threat types, but also at the ability of a typical surface force composed of numbers of ship types and classes that could reasonably be assumed to represent the assets that might be assembled to carry out naval missions in the face of air opposition. In view of the limited means for force coordination at the time, the degree of coordination of these hypothetical forces was treated as one of the study variables. Over the years, those studies clearly showed the significant increase in effectiveness that close force coordination could provide, particularly in ECM environments.[11]

In 1973, Al Eaton had made a presentation to a national symposium that included calculations (provided by Richard Hunt) that showed the possibility of force coordination, with the Aegis system as the basis. Thus, a long-term APL goal was to find a means to provide the Navy a way to effect the national motto, *E pluribus unum.*

In 1978, recognizing the superior fidelity of the air-situation picture that an Aegis ship would provide to a force, the NAVSEA (Naval Sea Systems Command) Aegis Shipbuilding Program Manager (Rear Admiral Wayne Meyer) established the Aegis Battle Group AAW Coordination (BGAAWC) Program. As the Navy's Technical Direction Agent, APL was charged with the identification and execution of technical activities directed at ensuring proper integration of the Aegis cruisers with other ships of the battle force, so that these benefits would be realized. In response to this challenge, APL, led by George Luke and Chester Phillips, focused on the definition and development of the facilities to be provided by the Aegis Display System (Fig. 18) to support a battle-group antiair-warfare commander. Efforts were also initiated to develop educational materials for use in informing the operating forces of Aegis and its capabilities. As a part of this missionary effort, APL placed resident representatives at major fleet commands who, as members of the fleet commander's staff, functioned to facilitate the technical process of introduction.

In the early 1980s, designs for display and control features to support AAW command in Aegis ships were being developed, aided by experiments in the Combat Systems Evaluation Laboratory at APL and in the USS *Norton Sound* at sea. A three-phase technical development plan was adopted to evolve the required capabilities using the proven build-a-little, test-a-little approach.[12] The first phase addressed the need to provide the force with a common, coherent picture of the tactical air situation. Based on the facilities provided by NTDS and its digital data link 11, an ongoing sequence of developments was initiated. The first step was to provide a practical means for each ship to continuously maintain an accurate knowledge of its location on, and orientation with, a common tactical coordinate system (a condition known in the fleet as being in gridlock).[13]

In 1983, APL tested an Automatic Gridlock Demonstration System in the USS *Kennedy*.[14] An essential element of this system was an effective ADT for the SPS-48 radar called the APL digital detection converter (a descendent of the system demonstrated on the SPS-48 radar at Mare Island in 1970). That digital detection converter provided the accurate, low-false-alarm-rate data on which success depended. The benefits of the equipment demonstrated in the *Kennedy* were so dramatic that the fleet clamored for expedited delivery of the system. Several advanced development models were assembled by APL to form a pool of equipment that could be rotated from ship to ship to provide the capability to forward-deployed carrier battle groups. Meanwhile, APL worked to effect an expeditious transfer of the knowledge and technology to appropriate Navy and industrial activities to enable them to rapidly produce the quantity of equipment needed.

Laboratory engineers led by Thomas Colligan, Robert Lundy, and Edward Lee continued to improve the fidelity of the force tactical picture by application of computer-based techniques.[15] Products of those efforts included demonstrations of airborne gridlock (for the E-2 airborne early warning aircraft), automatic track correlation (used by ships to determine whether or not a track is the same as one reported by another unit), passive gridlock (use of electronic support measures for gridlock), geodetic gridlock (alignment of the tactical grid to the geodetic grid), and automatic track identification (AUTO ID) (Fig. 19). Automatic track identification was first demonstrated in the USS *Forrestal* in 1988. As with automatic gridlock, the fleet demanded it right away; just as the gridlock rotating pool was being phased out, the AUTO ID pool was commissioned.

Under the APL Aegis program, managed by Thomas Colligan and Dennis Serpico, a number of developments of importance to BGAAWC as well as individual Aegis ships were pursued. Spurred on by the perennial low-flyer problem, the work of Harvey Ko and his colleagues in the APL Submarine Technology Department on modeling radar propagation in the atmosphere[16] was applied to the prediction of ship-system performance against specific threats based on local meteorological measure-

Figure 18. The Aegis display system. The complex system includes computer-driven large-screen displays, automated status boards, communication facilities, computer-control consoles, and a computer that is linked with shipboard weapons and sensors.

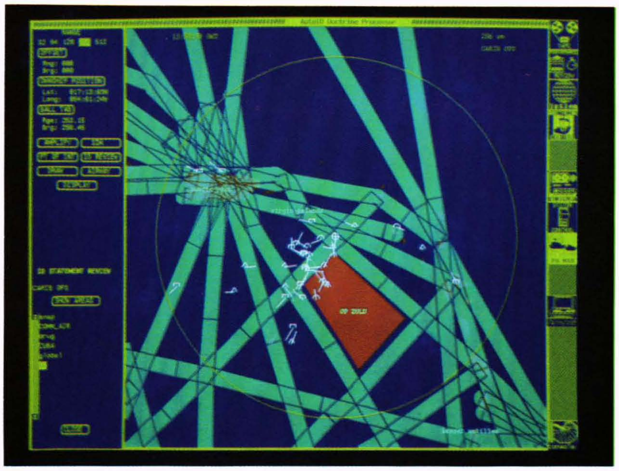


Figure 19. Operator display of the automatic identification system.

ments. The validity of those predictions has been verified in numerous flight tests and exercises at sea, and a prototype shipboard planning aid (SPAR) was demonstrated at sea.[17] A strong developmental program to continue the enhancement of the Aegis Display System complex has been prosecuted since 1985. That work has addressed the use of color, advanced graphics, and area maps to enhance comprehension. Of particular importance to BGAAWC is recent work to display over-the-horizon data on the current situation display using a prototype correlator/tracker.

Phase II of the BGAAWC plan addresses the need for extensive communications to coordinate the elements of a force. Early in the program, analysis showed that the NTDS link 11 and the Joint Tactical Information Distribution System (JTIDS), which is still in development, would not be able to support such BGAAWC concepts as remote launch (one ship initiating the launch of a missile from another and then controlling it to the target) or forward pass (one ship launching a missile and directing it to a point in space, where a second unit takes control and directs it to a target).

To meet the need, technical and operational concepts were identified, and in 1987 the Navy undertook the development of a concept called the cooperative engagement capability (CEC), with APL as its Technical Direction Agent. The CEC consists of two major equipments, the data distribution system and the cooperative engagement processor. The data distribution system incorporates advanced radio technology to provide cryptologically secure, jamming-resistant, line-of-sight, high-capacity digital-data interchange between units of a battle group. The cooperative engagement processor uses multiple digital processors to execute the routines required to manage inter-unit communications, to combine information from all units to provide a common comprehensive data base, and to effect coordinated direction of force actions. The CEC was successfully demonstrated using three engineering prototype unit sets, first at APL in 1989 and then at sea near Wallops Island, Virginia, in 1990. Recognizing the continued role of link 11 for some time, APL has developed and demonstrated a link 11 analyzer and multifrequency link 11 operation to enhance the operability of this important asset. Similarly, efforts directed at ensuring interoperability when both JTIDS and link 11 are being used are continuing.

A first small step toward the goal of Phase III of the BGAAWC effort—advanced weapon control—was taken in 1985 when the USS *Yorktown*, operating with the USS *Mahan* (Terrier NTU) and the USS *Turner* (Terrier SM-2), provided SPY-1 target data that enabled those ships to successfully engage air targets with their SM-2 missiles without using their search radars. Building on that remote-track/launch-on-search (RTLOS) technique, which was developed with the technical assistance of APL (William Mehlman), analytic work directed at identifying required changes to ship systems and operational concepts to effect remote launch operations are in progress. Similarly, work has been initiated to define the algorithms that should be recommended for Force Threat Evaluation and Weapon Assignment. Although following the Radcliff oracle ("nearest, least engaged") is obvious, the assignment of quantitative value to targets, units of the force, and assigned weapons is a challenge. This problem and the several others that lie in the path of achieving the goals of BGAAWC will be surmounted as the Navy/APL technical team perseveres.

CONCLUSION

The response of APL to the Navy's potential AAW requirements in the recently concluded period of tension and hostilities in the area of the Arabian peninsula perhaps best exemplifies its image of its mission to support the Navy. Using privileged available intelligence, appropriate AAW system responses to the several potential threats were analyzed and recommendations were provided. In response to fleet requests, knowledgeable APL experts went to the theater of operations to observe the situation and to provide recommendations. Ad hoc equipments were built to meet special needs, such as indicators of effective search radar coverage and additional AUTO ID outfits.

As incompletely outlined above, APL has for the past fifty years—in the best academic tradition—tenaciously pursued its original charge of "lending its brains" to apply science and technology to the air defense of the fleet. A central characteristic of those efforts has been the systematic employment of analysis and experimentation to understand the problem, to identify the technical means to address it, to develop practical means to solve it without concern for economic profit, and to transfer the knowledge gained to the Navy and its designated industrial contractors to enable efficient production and employment of the product.

The advent of space-based resources and other new tactical dimensions, coupled with evolving technologies, give the promise of providing effective counters to the diverse threats to naval forces that are now in gestation in the arsenals of potential enemies of the U.S., large and small. The coalition of university laboratory, government, and industry continues to be the most productive and dependable vehicle to exploit this promise.

REFERENCES

[1]Oliver, M. E., and Sweet, W. N., "Standard Missile: The Common Denominator," *Johns Hopkins APL Tech. Dig.* **2**, 283-288 (1981).

[2]Walker, B. S., "Push-Button War," *The Johns Hopkins Magazine* **XV**, 10-ff., (1964).

[3]Bruns, R. W., and Jarrell, E. C., "RAM Guided Missile Weapon System," *Johns Hopkins APL Tech Dig.* **2**, 200–206 (1981).

[4]Flanagan, J. D., and Sweet, W. N., "Aegis: Advanced Surface Missile System," *Johns Hopkins APL Tech. Dig.* **2**, 243-245 (1981).

[5]Phillips, C. C., "Aegis: Advanced Multi-Function Array Radar," *Johns Hopkins APL Tech. Dig.* **2**, 246-249 (1981).

[6]Irzinski, E. P., "APL Contributions To Aegis," *Johns Hopkins APL Tech. Dig.* **2**, 250-255 (1981).

[7]Flanagan, J. D., and Luke, G. W., "Aegis: Newest Line of Navy Defense," *Johns Hopkins APL Tech. Dig.* **2**, 237-242 (1981).

[8]Frekko, E. A.," Terrier/Tartar: Demonstration of AN/SYS-1 Integrated Automatic Detection and Tracking System," *Johns Hopkins APL Tech. Dig.* **2**, 268-275 (1981).

[9]Witte, R. W., and McDonald, R. L., "Standard Missile: Guidance System Development," *Johns Hopkins APL Tech. Dig.* **2**, 289-298 (1981).

[10]Betzer, T. A., "Terrier/Tartar: New Threat Upgrade Program," *Johns Hopkins APL Tech. Dig.* **2**, 276-282 (1981).

[11]Eaton, A. R., "What Does Technology Offer?", presented at Joint AIAA/AOA Tactical Missile Conf., Orlando, Florida (Mar 1973).

[12]Farris, R. S., and Hunt, R. J., "Battle Group Air Defense Analysis," *Johns Hopkins APL Tech. Dig.* **2**, 302-307 (1981).

[13]Phillips, C. C., and Prettyman, E. C., "Battle Group Antiair Warfare Coordination," *Johns Hopkins APL Tech. Dig.* **2**, 308-313 (1981).

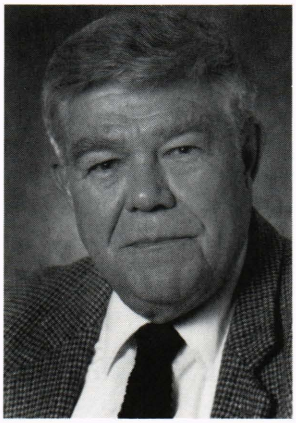
[14]Miller, J. T., and David, E. W. G., "Battle Group Gridlock Demonstration," *Johns Hopkins APL Tech. Dig.* **2**, 314-320 (1981).

[15]Miller, J. T., Lee, E. P., Joice, A. B., and Brockman, K. D., "Battle Group Gridlock–An Update," *Johns Hopkins APL Tech. Dig.* **11**, 17-20 (1990).

[16]Ko, H. W., Sari, J. S., and Skura, J. E., "Anomalous Microwave Propagation Through Atmospheric Ducts," *Johns Hopkins APL Tech. Dig.* **4**, 12-21 (1983).

[17]Emch, G. F., "Fleet Air Defense and Technology," *Johns Hopkins APL Tech. Dig.* **11**, 8-16 (1990).

THE AUTHOR



GEORGE F. EMCH received his B.S. degree in 1947 from Trinity College, Hartford, Conn. Mr. Emch joined APL in 1948 as an Associate Physicist and specialized in the employment of analog computers in the dynamic analysis of guided missiles. In 1959, as Project Engineer, he was responsible for the development and operation of the APL Electronic Countermeasures Battle Simulator. Shortly after his appointment as the Assistant Group Supervisor in the Bumblebee Dynamics Group in 1962, he joined the newly created Fleet Systems Department, where he served first as the Assistant Group Supervisor and then as the Group Supervisor of a progression of groups specializing in the detection and control elements of combat systems. He was the Assistant Supervisor of the Surface Combat Systems Program Office before his retirement in 1990.