ALEXANDER KOSSIAKOFF

APL—EXPANDING THE LIMITS

Throughout the fifty years of its existence, APL has compiled an extraordinary record of accomplishment in an ever-widening range of endeavors. Besides the sheer number and importance of its contributions, it is striking how many of them have embodied an entirely new concept, a new level of understanding, a new way to approach a hitherto unsolved problem, or a new direction for the Laboratory. And yet APL's primary mission has always been to solve problems of national importance, rather than to advance knowledge or technology for its own sake. Why, then, does innovation characterize so many of APL's accomplishments?

The answer, I believe, lies in an unstated but fundamental operating principle—one that challenges limitations standing in the way of an important objective. This principle may be called "Expanding the Limits." Its successful application has been responsible in large measure for the many "firsts" that have marked APL's contributions. In this fifieth year of APL's history, it is appropriate to take a retrospective look at how this characteristic has shaped the Laboratory's history and accomplishments.

The term "limits" as it is used here includes any constraints—physical, technical, institutional, contractual, traditional, political—that are actual or perceived obstacles to a desired goal. My thesis is that a dominant APL characteristic has been to challenge and seek to overcome all constraints that are not recognized to be fundamental and immutable.

The Laboratory's achievements during the past half century have been so prodigious that no brief account can possibly do justice even to the most important ones. The sections that follow are intended only to exemplify the diverse ways in which the impulse to expand the limits has shaped APL's missions and products over the past fifty years.

The general sequence of this paper is roughly chronological, but it often follows one theme well beyond the beginning of the next one for the sake of continuity. Because the point of view of this article is institutional and since APL's method of operation is based on teamwork at all levels, the names of all individuals have been purposely omitted. I extend my sincere apologies to those whose proudest achievements are not given due prominence in this article. Perhaps they will find that the much fuller account of APL's accomplishments contained in the other articles in this issue makes up for this deficiency.

ACHIEVING THE IMPOSSIBLE—THE VT FUZE

The character of the Applied Physics Laboratory was molded by the mission that it was organized to accomplish: the development of the radio proximity fuze, known for security reasons as the VT (variable time) fuze.

The development of the radio proximity fuze has been recognized as one of the most important breakthroughs in military capability of World War II. The technical obstacles faced by its developers were enormous (stuffing a radio into a tiny space in the nose of a shell, shocked by a blast of 20,000 *g*), so enormous that the Germans considered it hopeless and the British concentrated instead on radio fuzes for the "gentler" environment of rockets and bombs. It was characteristic of the founders of APL that they undertook to challenge these physical limits. I suspect that they did so because most of the technical leaders were physicists, accustomed to working at the limits of knowledge and without much respect for engineering "details." So the idea of designing a tiny vacuum tube that would withstand the crushing shock of being fired from a gun did not seem impossible, as it did to most others, but merely difficult.

The design of an ultrarugged vacuum tube was only the first "impossible" step in the process of fielding a successful weapon. The next was to mass-produce the fuze by the millions. This required a transition from development to production, solving along the way such critical problems as guaranteeing absolute safety from premature detonation in the gun barrel. To achieve such an objective on a crash basis required a new approach in organization—one that transcended traditional institutional boundaries. A team of universities and industrial companies was assembled under Navy contracts, and APL was established as a central laboratory, with responsibility for technically directing the development and monitoring the production effort. This unique experiment in teamwork under APL leadership was outstandingly successful in achieving its goals. The "Section T Pattern," as it came to be called, was a major innovation in the organization of large-scale research and development. It was to endure as an operational pattern for APL.

The third "impossible" feat of the wartime APL was the introduction of the new weapons into service in an incredibly short time. The first Navy fuzes were used in combat in January 1943 at Guadalcanal by the USS *Helena*. Key APL technical staff were sent to the Pacific to help introduce the weapons to the fleet, demonstrating the APL policy that "our moral responsibility extends all the way to the first battle use"—another example of expanding the limits.

The fuze not only played a major role in the destruction of the Japanese Naval Air Forces in the Pacific, but also was largely responsible for defeating the V-1 buzz-bomb attacks in London and Antwerp and for turning back the last German offensive, the Battle of the Bulge.

The fact that the fuze was perfected and available by the time it was needed was the crowning measure of APL's true contribution.

REACHING INTO THE UNKNOWN—GUIDED MISSILES

The successful deployment of proximity fuzes was estimated to boost the effectiveness of antiaircraft guns fourfold, but they still couldn't defend ships effectively from aircraft that maneuvered or those that released guided bombs from beyond the range of gunfire. It was evident to the Navy and to APL that the defense of the fleet from air attack required an increase in gun-pointing accuracy in the presence of pitch and roll and, more importantly, a means for following a maneuvering target during the shell's flight. An approach to the first objective was the development by APL of the Mk 57 gun director for the 5"38 naval gun. The second objective could be achieved only by an entirely new type of weapon—a missile that could change its course when the target maneuvered—that is, an antiaircraft guided missile. It was also necessary for such a missile to fly far enough and fast enough to intercept an enemy airplane before it could launch an antiship missile. In December 1944, APL's mission was officially extended to include the development of a family of such missiles.

The impact of this expansion in APL's responsibility on the nature and magnitude of its tasks was profound because no such weapon had ever been developed. More significantly, there was literally no technological base for designing a missile with the necessary characteristics: long-range guided flight at supersonic speeds. The new goal required that several very different technologies be explored and that a sufficient body of new knowledge be acquired to form a rational basis for engineering design.

The greatest advances were required in the fields of jet propulsion, supersonic aerodynamics and control, and missile guidance, all infant technologies. Not only was fundamental knowledge lacking in these fields, but even the underlying physics was unexplored because of the complexity of the processes of combustion, fluid dynamics, and radar propagation. Without established underlying theory, it was necessary to determine empirical relationships on which design could be based with some confidence. To do so required devising facilities to test experimental models of jet engines, aerodynamic shapes and guidance environments, and a vast accumulation of test data. As the war ended, APL was already creating a group of test facilities to establish an experimental basis for designing the propulsion and supersonic aerodynamic elements of the new weapons, to expand the limits of knowledge underlying guided missile design.

DEFYING INSTITUTIONAL TRADITIONS—APL AND THE JOHNS HOPKINS UNIVERSITY

At the conclusion of World War II, the Office of Scientific Research and Development (OSRD)—the agency that had mobilized the nation's universities and other research establishments on behalf of the war effort—was dissolved, as were virtually all the wartime university laboratories. Many laboratories, like Harvard's Underwater Sound Laboratory, were transformed into government establishments. Others, such as MIT's Radiation Laboratory, were disbanded, their staff returning to their academic posts.

A year before the war's end, the APL contract with OSRD had been transferred to the Navy in keeping with the large effort needed to put the VT fuze into production. As stated earlier, APL had also undertaken the major new task of developing guided missiles for defense of the fleet. In keeping with these special circumstances, the Secretary of the Navy, James Forrestal, asked Isaiah Bowman, President of The Johns Hopkins University, to accept a one-year extension of the University's contract with the Bureau of Ordnance to "enable certain activities of The Johns Hopkins University and its group of associated contractors to be carried forward effectively during a critical period of transition from war to peace."

The Forrestal letter created a virtually unprecedented situation and recalled the period after World War I when the nation experienced strong antiwar reaction. It also presented the University with the potential continuing commitment for managing a very large organization without the financial resources necessary to support it in case of need. Nevertheless, the Johns Hopkins President and Trustees accepted the Navy's request to extend its operation of APL into peacetime. This decision made Johns Hopkins one of the very few universities to retain responsibility for a large defense research laboratory in peacetime.

During the transitional period, Johns Hopkins brought in an industrial partner, the Kellex Corporation, to assume engineering and other responsibilities beyond the normal scope of an academic institution. The agreed-upon plan for the joint operation of APL was that Johns Hopkins would retain a nucleus of about 250 key scientists and engineers to exercise the central laboratory technical direction functions, as well as to conduct research in critical areas. The remainder would transfer to the Kellex payroll. Kellex was to assume custody of the buildings and equipment, perform engineering and test functions, and provide administrative and technical services. The administration was to be such that the average staff member would not notice any difference because of his organizational affiliation.

This experiment in dual institutional management encountered difficulties because of inherent fundamental differences in goals and outlook between a university and an industrial organization. As a result, disagreements developed in critical areas of Laboratory operations, producing increasing tension and uncertainty in the future on the part of the APL staff. In the summer of 1948, matters came to a head, and the President of the University with the support of the Trustees moved to restore the University's full responsibility for APL and to dissolve the joint operation. Kellex was given a Navy contract to carry out certain engineering service functions; the organization continues to this day as the Vitro Corporation. Most of the staff who had transferred to Kellex returned to the Johns Hopkins payroll.

The decision by Johns Hopkins to reassume responsibility for APL was far more significant than just a restoration of its wartime role. It was based on a more fundamental consideration, namely, whether or not the Johns Hopkins tradition of public service should be expanded to include the application of research to problems of national defense, in peacetime as well as wartime. The President and Trustees decided that it should and therefore conferred on APL the status of a permanent division of the University, on a level with the School of Arts and Sciences, the School of Medicine, and the other academic divisions. This decision, which expanded the limits of the University's public service mission, has shaped the character of APL as no other has done.

The importance to APL of being a regular division of a first-rank university cannot be overstated. No other university laboratory of comparable size enjoys such a status, all others having a special status outside the normal university structure. The question is regularly asked why the Laboratory should not be split off (as indeed MIT's Draper Laboratory was) or disbanded or its defense-related work terminated. Indeed, during the student protests of the 60s, several universities yielded to pressures to sever their connections, but APL's role was never seriously threatened.

"THE BUMBLEBEE CANNOT FLY"

To answer the challenge posed by the lack of scientific and engineering foundations for developing guided missiles to defend the fleet, APL applied the Section T type of centrally-led university–industry teaming that had proved so successful for the fuze (see Fig. 1). The collaborating organizations were called associate contractors; their contracts specified that their tasks would be under the technical direction of APL. Under this unusual arrangement, APL was free of the responsibility of administering the financial and business affairs of the contractors and could concentrate on leading the technical activities. The program was given the name Bumblebee.

In keeping with the exploratory nature of much of the research and development effort, Bumblebee Technical Panels were established in the areas of principal activity: aerodynamics, guidance, launching, propulsion, and composite design. The panels proved to be invaluable means of technical communication and significantly accelerated the creation of a technical basis for missile design and engineering. Of the three services, the Navy was the only one to sponsor a comprehensive research and development program in support of its guided missile effort. As a result, the Bumblebee program served to lay the technological foundations for much of the entire U.S. missile development, especially in the fields of supersonic aerodynamics and control, jet propulsion, radar guidance, solid rockets, and telemetry. Thus, expanding the limits of guided missile technology was accomplished through the medium of a novel form of institutional collaboration.

The means of propulsion selected to power the primary long-range Bumblebee missile, called Talos, was characteristic of APL's disregard for conventional limits. It was the ramjet, an unproven French invention with an opening in the front to let in air, a combustion chamber in the middle to heat the air, and an opening in the rear to exhaust the products. Whether such an "engine" would create thrust greater than its aerodynamic drag was itself in doubt, let alone its capability to propel a guidance and control system and a payload. But if it could do these things, the ramjet engine offered very efficient propulsion at supersonic speeds and thus the potential of much longer ranges than could then be expected from rocket propulsion. The name of the program was very aptly derived from the aphorism: "The Bumblebee Cannot Fly. According to recognized aerotechnical tests, the bumblebee cannot fly because of the shape and weight of its body. But,

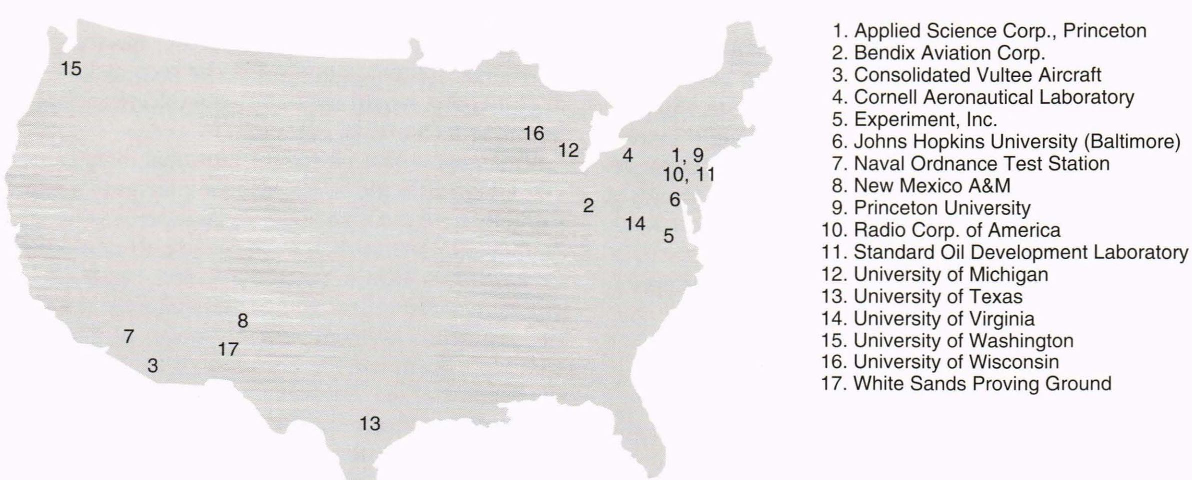


Figure 1. The Section T Bumblebee organization, a unique and successful innovation in the organization of large-scale R&D programs, with APL serving as a central laboratory technically directing the efforts of a group of leading university and industrial organizations and Navy test facilities, laid the foundation for much of U.S. guided missile technology (list as of 1953).

the bumblebee doesn't know this, so it goes ahead and flies anyway!"

To design the ramjet combustion system and airframe, data were needed that were neither available nor calculable from existing theory. Under APL direction, a large-scale combustion research facility as well as a supersonic wind tunnel were designed and constructed at Daingerfield, Texas. The Ordnance Aerophysics Laboratory, as it was called, was a premier ramjet and aerodynamic test facility in the 50s and 60s, used by agencies of all three services. A smaller burner test facility was also built at APL. Flight ranges to try out missile propulsion and other components in their natural environment were constructed. The Laboratory also pioneered in telemetry—the design of flight instrumentation that measured and transmitted to the ground for analysis data on the performance of critical missile components during flight.

Proof of principle of the ramjet was demonstrated in flight within a year of the program's beginning. The development of a full-scale Talos guided missile prototype was a much greater task and required about ten years. The associate contractors shared in engineering the major components, such as the missile airframe and control, propulsion system, guidance, warhead, and rocket booster. The airframe and propulsion systems were engineered by an aircraft company that later integrated and tested the entire missile. The Talos guidance system was especially challenging because it had to be effective beyond ranges where radar guidance was sufficiently accurate. The solution proved to be an "interferometer" homing system, based on an MIT invention that admirably fitted around the annular inlet of the missile. The system turned out to be remarkably accurate, producing direct hits on the target in a large fraction of missile intercepts.

BREAKING A PRODUCTION BOTTLENECK

The original Terrier missile was a spin-off of the Talos program to meet the Navy's desire for an earlier antiair capability than Talos could provide. The radically new Talos ramjet engine clearly required years of development. The test vehicle built to test the supersonic guidance and control elements of Talos, however, was powered by a solid propellant rocket with relatively proven performance. Although its range was only a fraction of the Talos objective, it far exceeded the effective range of naval antiair weapons and was deemed acceptable for an initial weapon. A program of stepwise evolution from a test vehicle to a prototype missile was undertaken, with Convair as the associate contractor responsible for airframe design and missile integration. In 1952, a test missile armed with an experimental warhead was successfully guided to a lethal intercept with a target drone.

In 1950, Convair, the associate contractor who had built the airframes for the test vehicles, was given a Navy contract to build a prototype of the missile. Operating on the notion that the developer "never stops perfecting his creation," APL's function was officially limited to flight test planning and analysis.

The orderly program of Terrier product engineering was overtaken by the outbreak of the Korean War when the Department of Defense ordered the Army and Navy to put three missiles into mass production, including Terrier. Convair was given a contract to build a huge missile engineering and production plant and to produce 1000 missiles at a rate of 75 per month.

The crash program to bring Terrier into production very nearly foundered. Missiles assembled for factory checkout revealed a multitude of faults that made them unable to pass final acceptance tests. Confidence in the missile design was further shaken by a rash of mysterious and spectacular flight failures of test missiles. The Navy felt compelled to set up an emergency organization, the Terrier Task Group, headed by the captain responsible for guided missile programs, to assume direct management of the engineering and production contract. The Laboratory was brought in as a pivotal participant.

The emergency caused APL once more to expand its interest from development to production. A team of twenty-five engineers was dispatched to help Convair diagnose the sources of production and testing problems. The APL team soon became the primary catalyst for identifying problems and obtaining solutions.

During several months of intense effort, numerous remedies were instituted and the flight failure problem resolved; the threat of program cancellation diminished. It was clear to APL, however, that the missile design was intrinsically not suitable for production. The missile was designed, not surprisingly, like an airplane with the various functional parts mounted inside the airframe to minimize space and weight rather than to simplify production. APL concluded that a radical departure from the current missile configuration was necessary, substituting one that "sectionalized" the missile configuration into a set of functionally independent sections, each capable of being specified, produced, and tested so as to be interchangeable with similar sections.

To demonstrate the validity of this concept, APL undertook to carry out a sectionalized production design, in which selected contractors built the individual sections, that were then assembled and tested by Convair, all under APL direction. Ten missiles known as Terrier 1B were designed, built, and tested. Eight of the nine fired in flight were entirely successful—an unheard-of reliability for that time. More importantly, the advantages of the sectionalized configuration were fully realized. Ultimately, this basic concept was incorporated by Convair into the production of subsequent lots of Terrier missiles and eventually accepted by many other missile programs.

HARNESSING THE DISCIPLINES—MISSILE SYSTEM ENGINEERING

The development of guided missiles not only needed the creation of an entirely new technological base, but also required the application of system engineering to an unprecedented degree. System (or systems) engineering is the method by which the requirements of a system are analyzed and validated; the most appropriate concept selected from the available technical options; the functional design laid out so as to produce the simplest interfaces among the interacting parts; and the design translated into reliable, producible, and testable elements that fit together into an effective overall system. The initial formulation of the system engineering approach was spurred by the wartime introduction of complex military systems that could be successfully developed only by a total system approach.

A central problem in applying the system engineering method is that traditional engineering disciplines are structured along highly specialized lines, and their practitioners are professionally motivated to push the specialization as far as practicable. A system whose elements require a blend of different disciplines places them in competition for precedence. The engineering of a guided missile requires a combination of mechanical, electrical, and aeronautical engineering, along with the application of propellants and explosives, advanced materials, servomechanisms, microwave devices, fluid dynamics, statistics, and telemetry. The proper balance among these disciplines and technologies is a challenge that calls on the highest system engineering skills imaginable (see Fig. 2).

One of the best examples of APL's applications of the system engineering approach was the design of the Terrier II missile, the follow-on to the initial design that had been converted from a Talos test vehicle. The main objective was to increase the missile's effectiveness against high-altitude and high-performance targets, which called for increased maneuverability. Terrier I, which steered by moving its wings, could not also use body lift without becoming aerodynamically unstable. Terrier II's solution was to use the missile tails for steering, keeping the wings fixed. A further and more radical change was to replace the wings by very-low-aspect dorsal fins running along the length of the body. This highly unusual design was initially derided by conventional aerodynamicists, but later became widely adopted. An important advantage of this design was its low dependence on the location of the missile center of gravity, making it possible to design a missile capable of operating with interchangeable warheads and guidance systems, with only minor adjustments in the missile autopilot. A major feature of the tail-controlled Terrier missile was the achievement of broad control-system tolerances, making the system more reliable and easier to manufacture than its predecessors, an innovation that profoundly affected the evolutionary growth of the Navy's air defense missiles to the present time.

The sectionalized tail control design of Terrier not only made it possible to evolve the Terrier missile through a series of improvements, maintaining the same basic configuration, but its configuration was ideal in filling the Navy's need for a highly compact antiaircraft system for destroyers. This adaptation was accomplished simply by removing the booster and modifying the sustainer rocket to provide both boost and sustained thrust during flight. Otherwise, Tartar had exactly the same guidance, control, warhead, and auxiliary systems as Terrier. The production economies of this unified design were enormous because the common sections could be produced on the assembly line without regard for their destination thus realizing the economies of scale and standardization (see Fig. 3).

The lessons learned in system engineering during APL's early days became an article of faith in subsequent endeavors. The system view and the emphasis on meeting real operational needs have been decisive factors in the remarkable productivity of the Laboratory in terms of truly significant contributions during its lifetime.

SCIENTIFIC ANALYSIS OF AN OPERATIONAL SYSTEM

During the late 40s and 50s, APL's technical programs broadened in both technological and operational scope, moving from the proximity fuze to guided missiles and ship systems. The general objective, however, remained focused on the defense of the fleet from air attack. In the late 50s, two new programs developed that were to

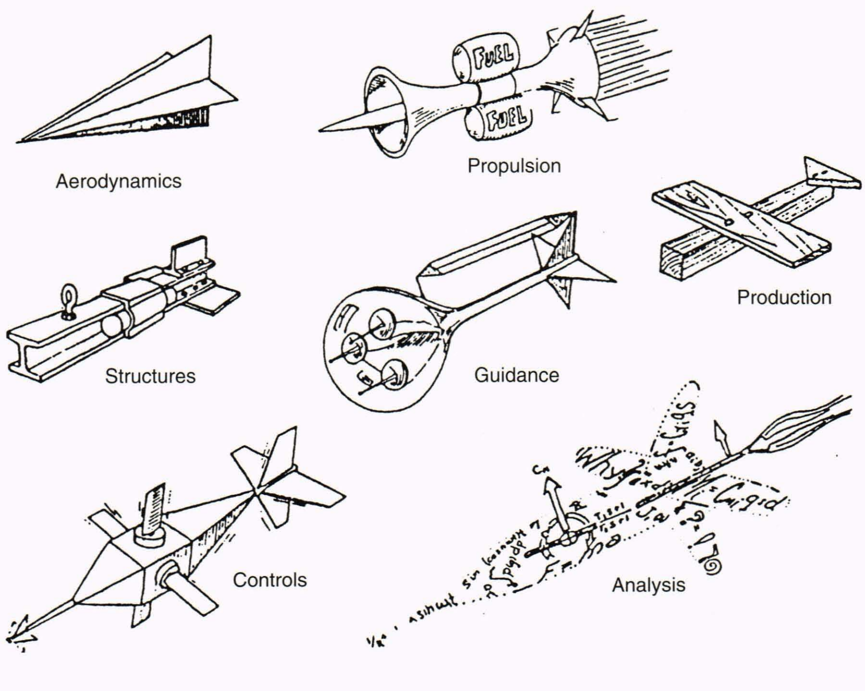


Figure 2. Guided missile system engineering. The guided missile involves an unusually large number of diverse disciplines that must all be combined in a harmonious and balanced way to produce an effective design. The striving of the various specialists to optimize the design to their ambitions, as illustrated in the figure, must be adroitly and firmly tuned to the common good. System engineers at APL have been notably successful in this regard.

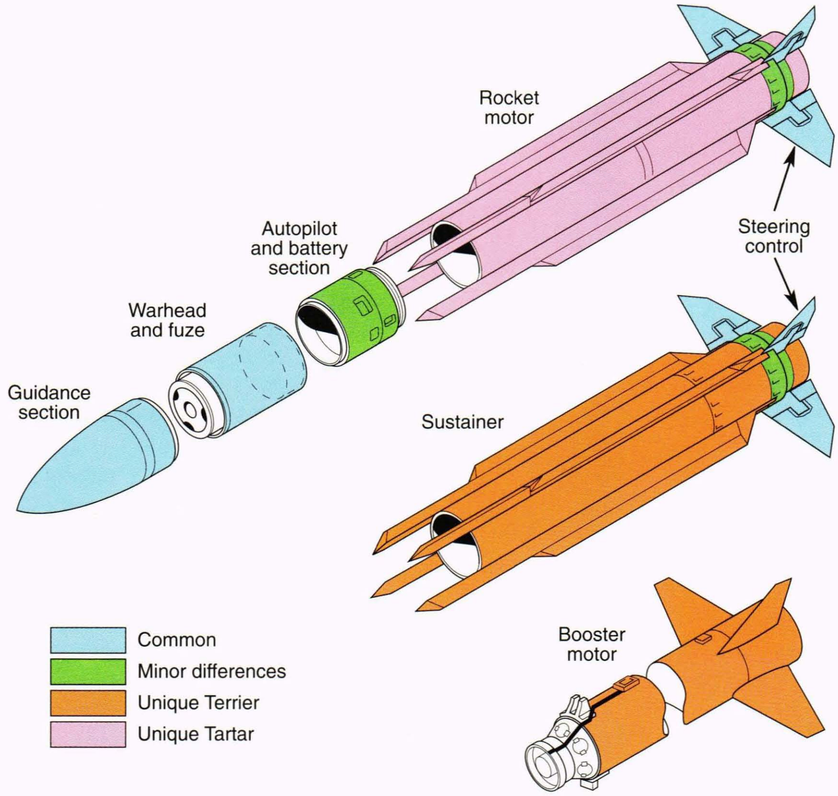


Figure 3. The Terrier–Tartar commonality and sectionalization were breakthroughs in guided missile system engineering that enabled the Navy to equip its guided missile fleet with missiles that could fit in both small and large ships, provide extended- or medium-depth defense, and yet be manufactured on a single production line with identical critical guidance and control components.

become permanent mission areas. At the same time, the character of APL's work in the air defense area gradually shifted from concentration on missiles to an emphasis on ship systems and their integration. These events together caused a major growth and diversification in APL's activities.

The first new mission came in response to a request for technical assistance early in the Navy's development of the Polaris fleet ballistic missile system. The Polaris program had been initiated to form an essential component of the U.S. "triad" of strategic deterrent weapons. The Navy mobilized its most experienced and talented civilians and officers under the Special Project Office to direct the effort and created a contractor team to carry out the development. Because of its experience in shipboard missile systems and demonstrated analytical skills, APL was asked to provide consultation to the Technical Director. In 1958, APL's role was expanded to that of devising and conducting a continuing evaluation of the total Polaris system. The evaluation was to be the most comprehensive and precise ever attempted, to give the Navy and the Joint Chiefs of Staff a high-confidence measure of the system's performance and readiness. The Laboratory's experience in missile design, testing, and analysis; its understanding of operational systems; and its expertise in telemetry, instrumentation, and computer simulation made it uniquely capable of undertaking this task.

The Polaris concept was itself an extraordinarily challenging objective. The Navy had decided to use a solid rocket to power the missile because the potential hazard posed by liquid rocket propellants aboard a submarine was deemed unacceptable. No solid rocket existed in a size and efficiency at all comparable to that required to hurl the large Polaris warhead to a target over 1000 miles away. Furthermore, the mechanism of solid propellant burning was not well understood, and not infrequently a rocket in flight would begin to burn uncontrollably for no apparent reason and burst violently in midair.

The Polaris missile was to be guided in flight by onboard gyroscopes and accelerometers, but no such components had yet been developed with nearly the accuracy required to make the missile effective. The missile was to be launched under water by a compressed air charge and ignited just after emerging, all the while maintaining a precise guidance reference. And a rocket malfunction at this time could be fatal to the submarine.

This combination required all Polaris system components to be accurately modeled for extensive analysis, entirely new test instruments and methods to be devised, and special analytical facilities developed. The technical problems of the Polaris evaluation were not susceptible to straightforward engineering approaches. Since the missile system elements were designed to be as accurate as the state of the art would permit, measuring the system performance required instrumentation severalfold more precise. Also, the high cost of the missiles made it mandatory that reliable conclusions be drawn from a handful of tests. This required that the tests be planned as scientific experiments, with extraordinary attention to detail. The successful achievement of these objectives by the APL Polaris team expanded the science and art of system evaluation to new levels. The knowledge gained in the Polaris evaluation program was an important element in the extraordinary success of the program in meeting all its objectives and in its continued decisive contribution to the U.S. strategic deterrent.

The Polaris evaluation task was a totally new role for APL—one of assessing someone else's technical product rather than its own, nor did it appear to offer the opportunity to innovate that the Bumblebee program had done. But the national importance of the Navy's strategic deterrent and the technical challenges involved in devising complex and high-performance instrumentation necessary for the task were strong motivations. Moreover, the close working relations with Navy operational and test personnel made for a new kind of teamwork that was highly rewarding. In later years, the scope of the Polaris task expanded and led to another new mission for APL: submarine technology.

To the Navy, APL qualities that have been of priceless value are its independence of outlook and unquestioned integrity. Like the other services, the Navy insists on a totally independent evaluation of its new systems and delegates this function to a special unit, the Operational Test and Evaluation Force. Only the Polaris system is allowed to be evaluated by its program management agency, the Special Project Office, a circumstance that attests to the widespread recognition of APL's independence and competence. No one has ever questioned the complete authenticity and dependability of APL's assessment of Polaris system performance, either in individual tests or at the overall fleetwide level.

Characteristically, APL's contributions to the Polaris program have not been confined to its principal function, system evaluation. At the outset of the program, APL scientists were asked to lead an intensive research effort to gain an understanding and possibly a remedy for the occasional tendency of solid rockets to lapse into unstable burning with often catastrophic results. This tendency manifested itself most often in rockets using advanced high-performance propellants such as those needed for the Polaris missile. The effort produced a theory that explained how a subtle coupling between acoustic waves in a rocket chamber and a burning propellant could amplify the waves to produce burning instability. The theory provided a sound basis for designing solid rockets that were free of the problem. The Technical Director of the Polaris program stated that "As a result, incalculable savings have been realized in the Polaris, Poseidon and Minuteman programs."

PENETRATING THE SPACE FRONTIER

Months before the Russians startled the world by launching their Sputnik satellite, APL had already decided that space might well be a new frontier for the Laboratory. In the summer of 1957, it was decided to take a serious look into potential future technology areas that might offer new opportunities in solving important national problems. After a series of weekly seminars involving a dozen of APL's top technical managers, three areas were identified, and small groups were established to pursue them in depth. A plasma physics group was established to explore system aspects of hydrogen fusion energy to which APL might apply its expertise in system engineering. A "thinking machine" group was set up to investigate the theory and practice of self-organizing devices (thinking machines). And a space study group assessed potential uses of space for military and civilian purposes.

The story of the birth of the Transit satellite navigation system has been recounted many times and is known to everyone associated with APL. But it is less well known that the momentum generated by the APL space study group contributed to the remarkable speed with which the Transit concept was put into practice. The experience gained by APL engineers in designing guided missiles to withstand the shock and vibration of rocket launching, as well as in designing reliable complex electronics, was directly responsible for the success of APL-designed satellites from the very beginning.

The success of the Transit navigation system represented "expanding the limits" of several areas of technology. The very concept of being able to compute a location on Earth by observing the change in frequency of a satellite-borne transmitter during a single pass was initially ridiculed by a number of reputable scientists. Achieving the desired accuracy required the development of a time standard several orders of magnitude more precise than existing devices. Today, APL-built stable crystal oscillators are in widespread use and approach atomic clocks in accuracy. To compensate for the local variations in the Earth's gravity field, APL created a comprehensive model of that field (and hence of the Earth's shape) on the basis of data from hundreds of satellite passes. To eliminate errors caused by ionospheric refraction effects, a second frequency was introduced to enable the distortion to be cancelled out. The methods developed were so accurate that they were even able to compensate for platform motion automatically (see Fig. 4).

The Transit system pushed navigational accuracy to levels never before achieved, twenty-five years before the development of another satellite-based system, the Global Positioning System. Today it is used on thousands of commercial vessels as well as on Navy ships and submarines.

The expansion of the APL mission into space occurred when industry was becoming proficient in the engineering and production of guided missiles. It provided APL with a continuing area of hands-on design and experimental fabrication, with ever-present technical challenges.

COUNTERING SURPRISE, CONFUSION, AND SATURATION

In addition to its development activities, APL had evolved a tradition of continually assessing both the Navy's needs in its general area of responsibility and the effectiveness of systems proposed to meet these needs. From this perspective, evidence accumulated in 1957 that the evolving Soviet threat could challenge and possibly overwhelm the Navy's air defense as it was being constituted.

Because of the potential importance of this issue, a special APL group was established to conduct a comprehensive study of the Navy air threat and potential system concepts to meet it. The most serious element of the threat consisted of three parts: (1) low-altitude attacks by antiship missiles shielded from early detection by the radar

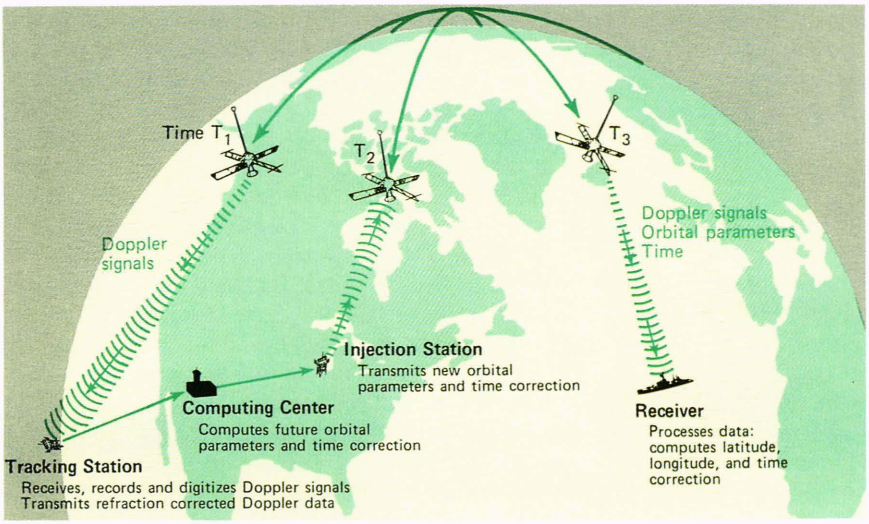


Figure 4. The Transit satellite navigation system provided the first highly accurate, worldwide, all-weather navigation system for ships and submarines. It was based on a novel principle unique to spacecraft and has revolutionized geodesy and global surveying.

horizon, (2) screening of the attacks by electronic countermeasures, and (3) launching of the missiles in coordinated formations. Such tactics would produce a combination of surprise, confusion, and saturation against which current shipboard radar could neither respond in time nor support sufficient missile intercepts to be effective.

The study produced a concept for a future ship defense system that would be built around a new type of radar that combined the functions of target detection (surveillance) and missile direction (fire control). To meet the requirements, the radar was to use electronic beam scanning, instead of a movable antenna, to realize a near-instantaneous response and be able to control a multiplicity of missiles directed toward several targets simultaneously. This multifunction array radar would also use very high power and frequency diversity to make it relatively invulnerable to electronic countermeasures. Two new missiles—to cover the long- and intermediate-range defense zones—were also proposed.

As had happened numerous times previously, this APL initiative projected the Laboratory's mission well beyond its designated limits in order to fulfill a critical operational need. The implications of the threat defined in the APL study persuaded the Bureau of Ordnance that such an integrated approach was necessary. Accordingly, a new program was authorized with the code name Typhon, under the technical direction of APL. Thus, APL had expanded its fleet defense mission to embrace the entire future antiair warfare weapon system.

The Typhon program was organized in the same manner as previous Bumblebee developments, with a group of associate contractors under APL technical direction. By 1959, construction of a prototype of the radically new phase array radar had begun, and by 1961 an engineering development model was being installed in an experimental ship for full-scale evaluation.

The price of the electronically scanned radar included the requirement for fixed phase array antennas fed by thousands of individual microwave amplifiers. It also required a complex computer program to control the radar beam pointing for the search and guidance modes of the radar. Meeting those requirements stressed the state of the art and led to difficulties during the system integration and test phase, resulting in program delays and cost increases.

Unfortunately, those problems coincided with an even more serious emergency that confronted the Navy when the first group of new Terrier ships began final tests before going into service. As will be described in the following section, these events forced a major reorganization of the entire guided missile effort and massive new funding to finance a remedial program. To secure the funds, the Navy cancelled a ship budgeted to receive the first Typhon. Not long thereafter, the Navy decided to terminate the Typhon development and redirect its resources to more immediate needs.

Since the threat that the Typhon system was intended to meet remained valid, the Navy established a formal requirement in 1963 for an advanced surface missile system (ASMS) with substantially the same general goals as those proposed in the original APL study. An ASMS assessment group was established by the Navy to synthesize a system design to meet the requirement. The result was a conceptual design based on the Typhon system as modified by experience and a reassessment of technological capabilities. The concept again called for a multifunction array radar, but of somewhat more conservative construction than the Typhon radar.

The ASMS program was approved by the Department of Defense in 1967, and a prime contractor was selected in 1969. In the intervening period, APL designed and built an experimental signal processor for the radar that accomplished the complex beam switching, signal detection, frequency management, ranging, and all other functions performed by the radar. The APL design was used as the basis for the contractor's implementation of the radar.

The Aegis program, as it became known, was successfully carried through development, engineering, and evaluation at sea. Thanks to the lessons learned in Typhon, no undue difficulties were encountered in its evolution into a fleet weapon. Construction of Aegis ships began in the

1980s, and they are scheduled to eventually replace the current fleet of guided missile destroyers and cruisers.

Having conceived and demonstrated the technical basis for the Aegis system, APL has served as program advisor to the Navy program manager.

CURING AN AILING GUIDED MISSILE FLEET OR MAKING UNWORKABLE SYSTEMS WORKABLE

On the strength of the successful resolution of the Terrier production bottleneck and installation of missile batteries on board the converted cruisers *Boston* and *Canberra*, as well as progress in the development of Talos and Tartar themselves, the Navy embarked in the late 50s on an accelerated shipbuilding program to create a modern guided missile fleet in minimum time. The schedule called for shipbuilding rates to reach one to two per month.

As the first group of Terrier guided missile ships was launched, system checkout operations were plagued by a rash of test failures attributable to a variety of equipment interface and reliability problems. Many difficulties were a result of inadequate attention to the integration of the missiles with their associated shipboard fire control radars and launchers before they were installed aboard ship. Others, such as faulty mutual alignment of the radar tracking and guidance beams, appeared for the first time aboard ship because they were not properly tested before acceptance at the factory. The fire control radars malfunctioned every few hours and remained inoperative for extended periods because they had not been designed for rapid repair at sea.

As the technical agent of the Navy's guided missile integration branch, APL became heavily involved in efforts to diagnose and remedy these problems. As it became apparent that more problems existed than could be handled by ordinary means, APL recommended that the Navy initiate a comprehensive remedial program. Calls for emergency action also came from high levels in the Navy, leading to the establishment of a special task force under the direction of a flag officer to manage the surface missile program. The Laboratory was asked to be the principal technical support organization, with the responsibility of technical direction of the ailing fire control and weapon direction systems, as well as the missiles. The Bell Telephone Laboratories, developer of the weapon designation equipment, also joined the task force.

Being a lead technical participant in the 3T improvement program, as it came to be known, was a far different role for APL than that of leading the Bumblebee development. Instead of blazing new trails in advanced technology, it involved going to sea for weeks, improvising experiments on board ship with makeshift instrumentation, coping with spare parts shortages—all with complex, unfamiliar equipment that would not work properly. With the pressure of a production line turning out a stream of new ships and ship systems, it seemed like the Terrier production crisis all over again, but on a far larger scale.

To provide a test bed for evaluating design fixes to the shipboard equipment, as well as longer-range modifications, APL constructed a radar building in its backyard that housed a complete Terrier radar and other elements of the weapon control system and surrounded it with towers for simulating targets and measuring radar characteristics. A Tartar weapon control system was added later. The facility was indispensable for acquiring a deep and detailed knowledge of the system elements and determining what modifications had to be made to meet system requirements.

In the ensuing years, the various performance and reliability problems of the 3T weapon systems gradually were understood; their causes identified; and remedial designs built, tested, and installed. It was a grueling period for the hundreds of APL engineers who were involved directly or indirectly, but the results were highly gratifying and the lessons learned were of enormous value. Most importantly, APL acquired a first-hand knowledge of the unique features of the shipboard environment and the problems of the people who had to operate the systems. The experience truly expanded APL's expertise to new limits.

As the more immediate problems of the weapon systems yielded to treatment, the limitations of the rest of the system became apparent to APL. The Laboratory's extensive participation in fleet exercises showed that a large fraction of simulated attacks was not detected by the search radar operators; many of those detected were not acquired by the fire control radar or were acquired too late to intercept. In the presence of jamming, bad weather, or nearby land, performance was particularly degraded. In short, the ship's search radar and associated manual detection and tracking operators did not adequately support the weapon system. The advanced radar planned for future ships was many years away and, in any case, would not be retrofittable on the dozens of 3T ships under construction.

The shipboard surveillance system traditionally had been the responsibility of the Bureau of Ships and was clearly outside the purview of APL as a technical arm of the Bureau of Ordnance. The Bureau of Ships took the position that a superior search radar, the SPS-48, scheduled for the later Terrier ships, would provide the answer. The new radar was too large to go on the Tartar ships, however, and APL doubted that it would solve the whole problem.

With encouragement but little financial support from the Bureau of Ordnance, APL went to work to understand the problem and attempt to find a near-term solution. A surplus predecessor of the SPS-39 3D search radar used on all Tartar ships was found in storage in Boston and installed atop the APL "ship." Recordings of radar operating in the Gulf of Tonkin were analyzed at APL as were reams of data on clutter characteristics accumulated during years of APL studies. All published work on radar operator performance was combed through. Two important conclusions emerged from these studies: (1) the ship's radars were inherently more capable than they were given credit for, but (2) the ability of the radar operators to handle more than two or three tracks, especially in the presence of clutter or other interference, was much more limited than generally believed.

Out of this work came a concept for an automatic detection and tracking system that could work with present radars despite all their limitations. The system consisted of a novel signal processing device called the adaptive video processor (AVP) coupled to a small modern digital computer. The AVP would filter out extended clutter and jamming while maintaining optimum sensitivity to discrete targets. The computer would process the AVP output to combine radar "hits" on successive scans into detections and then into target tracks. The radar operator would be relieved of the task of following every blip on the radar display and instead would supervise the performance of the automatic tracker operation by intervening when necessary to resolve marginal tracks.

The APL concept was implemented in an experimental radar detection system and demonstrated on land in 1970. On the basis of an evaluation of the land tests, APL was finally given a go-ahead to build a shipboard demonstration model. The SYS-1, as it was designated, was tested aboard the USS *Sommers* in 1973 and demonstrated performance an order of magnitude better than ever before achieved under comparable conditions.

This APL initiative had far-reaching effects in improving the capability of the pre-Aegis fleet, as well as laying the basis for Battle-Group Coordination some years later.

OVERCOMING INSTITUTIONAL CHALLENGES

Beginning in 1967 and for nearly ten years thereafter, APL was subjected to a period of close congressional scrutiny and constraint, along with a number of other organizations devoted entirely to defense work. The situation grew out of an inquiry by a congressional committee into the operations of a not-for-profit organization set up by the Air Force to perform system engineering and technical direction services. The committee took exception to some of that organization's management practices and requested the services to provide a list of all organizations that were engaged in similar activities. Unfortunately compiled without explicit guidelines, the list was interpreted to include all industrial or government organizations established to support the defense effort. The list was rapidly reduced to seventeen organizations that were called Federal Contract Research Centers (FCRCs). Included were four study and analysis organizations, two system engineering–technical direction organizations, and a number of university-operated laboratories.

Congressional action on the FCRCs was mainly focused on restraining their further growth through the establishment of individual ceilings for each organization, with the ceilings reviewed during the annual budgetary process. Four years previously, APL had decided to limit further staff growth because of the increasing uncertainties in the government funding process, so the zero-growth policy did not initially affect its operations. The greatest problems for APL in the early FCRC years came from the uncertainties of the annual ceiling assignments. Every few years, one or another congressional committee levied an across-the-board reduction of 5% to 10% because of a concern with an individual FCRC. Such cuts occurred late in the appropriation process and created disproportionately larger budgetary problems. In these instances, APL used the good offices of its local member of Congress and, on occasion, those of the entire Maryland Congressional Delegation to mitigate the impact of the cuts.

Throughout the FCRC years, the Laboratory contended that it and similar laboratories were not of concern to Congress and hence did not belong in the FCRC category. Congressional concern was clearly centered on nonprofit organizations created wholly to perform defense work and that were receiving special treatment from their service sponsors, and not on university laboratories that were part of independent institutions and subject to established controls. Efforts to have this position recognized were initially unsuccessful, however.

During the inflation of the 1970s, Congress permitted the FCRC ceilings to grow, but only half enough. By 1975, the squeeze of the ceilings, aggravated by double-digit inflation, forced the Laboratory to reduce operating costs by instituting emergency economies including a hiring freeze. Fortunately, the APL-led efforts to have university laboratories recognized as not requiring special congressional oversight finally bore fruit. In 1976, the Navy persuaded the Department of Defense to recommend that the three Navy university laboratories be excluded from the FCRC category, an action that was approved by Congress. Consequently, APL again succeeded in throwing off unwarranted limits on its ability to carry out its public service mission. The Laboratory's unique value to the Navy is clearly and unequivocally expressed in a statement to Congress by Assistant Secretary of the Navy for R&D, Robert A. Frosch, dated April 1971, an excerpt of which is reproduced here (first boxed insert).

The late 1960s also witnessed intense antidefense activity on many campuses to the extent that several major universities severed their connections with laboratories they had sponsored for many years. Some of the most significant instances were the severance of Draper Laboratory from MIT, Hudson Laboratory from Columbia, Cornell Aeronautics Laboratory from Cornell, and Stanford Research Institute from Stanford. With this background and the special interest shown by Congress, the Director of Defense Research and Engineering (DDR&E) asked the President of Johns Hopkins to state the degree of commitment of the University to the operation of APL.

There had been discussion of the APL defense mission by Johns Hopkins students and faculty, but there was only token organized opposition by a few individuals. In response to the DDR&E request, the President and Trustees drew up a "Statement on the Applied Physics Laboratory," which reaffirmed the University's commitment to the "application of advanced science and technology to the enhancement of the security of the United States of America . . ." through the Applied Physics Laboratory.

This statement, issued after extensive debate on defense activities on many campuses, once and for all put The Johns Hopkins University on record in support of APL's defense role as an integral part of its public service mission. In subsequent years, it has been an important symbol of the University's dedication and support. Excerpts from the Trustees resolution are contained in the second boxed insert.

STATEMENT BY ROBERT A. FROSCH

Written Statement of Hon. Robert A. Frosch, Assistant Secretary of the Navy, at the Request of the Committee on Armed Services of the U.S. Senate, Fiscal Year 1972 Hearings, Held April 1971, Part 3 of 5 Parts, pps. 2717–2720

There is no other organization in the United States (government in-house, university, or industrial) with experience in the problems of the Navy which has the breadth of demonstrated capability in science and engineering which is found at APL/JHU. The facilities of APL/JHU are not duplicated in-house or in industry. APL/JHU is the Navy's lead laboratory in fleet air defense, fleet ballistic missile systems evaluation, air penetration development, and space technology. The following paragraphs expand on these statements.

APL has developed comprehensive understanding of all aspects of missile and space technology, the peculiar problems and limitations of the shipboard environment and operating personnel, and the interactions of the various sections of the Navy organization. This depth of understanding is not available in any other organization. The technical staff of APL includes specialists in the specific scientific and engineering fields embodied in missile and space technology and, more particularly, has developed systems engineers capable of directing teams engaged in development of composite systems. Further, this Laboratory has a proven capability not only in R&D but also in the resolution of problems of production, of introduction of equipment into the fleet, of maintenance, and of logistics. The unique capabilities of the Applied Physics Laboratory stem from the body of knowledge, experience, data and facilities accumulated through several decades of highly diversified and outstanding technical work on Naval problems.

In applying its talents to the many diverse problems to meet Navy operational needs APL's efforts have been distinguished by the following special characteristics:

(a) Application of scientific methods to the technical evaluation of operational systems. The orientation toward formulating and analyzing critical experiments to obtain basic understanding of detailed system operation is associated with the general spirit of critical inquiry derived in part from the university association.

(b) Orientation of research to practical military objectives with the general policy of coupling research activities closely with applications to obtain products of direct applicability to Navy needs.

(c) System integration of complex ordnance devices involving multiple disciplines. APL has attracted and trained very versatile key project leaders capable of understanding the complex technology involved and making the compromises necessary to obtain a practical and balanced approach, leading to a product specification.

(d) Following complex technical programs through from concept to operational deployment.

UNRAVELING THE MYSTERIES OF THE SEA

In 1968, the Department of Defense requested the Navy to prosecute a basic and comprehensive program directed toward ensuring the continued survivability of the strategic submarine fleet. The effort, called the SSBN Security Technology Program (SSTP), was to investigate all phenomena that might be exploited by a potential enemy to detect submarines. The program was to marshal the efforts of organizations experienced in related fields and would be prosecuted vigorously in a coordinated manner.

The program's directing agency, the Navy's Special Project Office, asked APL to serve as the central laboratory and technical director of this program, much like in the Bumblebee era. The choice of APL instead of one of the Navy laboratories with many years' experience in antisubmarine technology attested to the importance attached to APL's intimate knowledge of the SSBN system, as well as its experience in leading large research and development programs. A team of university, industrial, and Navy laboratories was soon formed, and an intensive program was under way.

The Laboratory found that the basic understanding of the ocean environment was scanty and that the available technology was rudimentary, just as it had found the state of knowledge related to guided missiles. The ocean is an extremely complex medium, swirled by currents, structured in layers of varying salinity and temperature, with a surface swept by winds. Propagating sound waves, used for sonar detection, are refracted into zones with periods of many miles. An example of a major area of ignorance was the potential range of detection by passive sonar. Central to the problem was the achievable gain of an acoustic array. It was generally believed that the random motion of the ocean would limit the array gain to 17 dB (factor of 50). A major theoretical and experimental investigation by the SSTP in 1976 to 1978 conclusively demonstrated that the ocean's capability to support propagation is about 15 dB (30 times) greater than the assumed limit, a finding that provided an impetus to an expedited and successful U.S. effort to develop large-scale acoustic arrays.

Another basic problem concerned the capabilities of low-frequency active sonar, which radiates and senses frequencies below 1000 Hz. Conventional wisdom held that such systems would not be effective because of ocean propagation limitations. In the early 80s, the Soviets brought out submarines that were very much quieter than their predecessors, making it necessary to find a new way to counter them. A large-scale APL ocean experiment held in 1983 demonstrated that it was possible to insonify an ocean basin with low-frequency radiation such that submarines could be detected at great ranges. These APL-led experiments have spurred the Navy to give high priority to developing this technology.

In addition to extending the limits of knowledge and practice of acoustic submarine detection, equally significant extensions have been made in the knowledge of nonacoustic detection methods such as hydrodynamic,

THE TRUSTEES RESOLUTION

The Johns Hopkins University restates its firm dedication to the Applied Physics Laboratory and its defense mission as an integral part of the University in a statement by the Trustees, dated 8 January 1968, which is reproduced in part in the following.

STATEMENT ON THE
APPLIED PHYSICS LABORATORY

The general purpose of The Johns Hopkins University can be stated as public service through education, research and the application of knowledge to human affairs. As part of the University, the Applied Physics Laboratory shares this purpose through the application of advanced science and technology to the enhancement of the security of the United States of America and basic research to which its facilities can make an especially favorable contribution . . . .

At the conclusion of World War II, Secretary of the Navy James Forrestal (who subsequently became the first Secretary of Defense) made strong representations to the University to continue its operation of the Applied Physics Laboratory for the Navy. After a searching appraisal of the role appropriate to a University in peacetime in the conduct of national defense research and development, The Johns Hopkins University agreed to this request in the belief that certain types of applied research for defense purposes, together with basic research related thereto, could contribute to the general broadening of knowledge in keeping with the wider purposes of the University as well as directly serving the national security interest. This decision was later confirmed by granting APL the status of a Division of the University and the establishment of plans for its long term stability.

The Board of Trustees of the University has maintained continuing interest in the objectives and operations of the Laboratory. To this end there was appointed at the very beginning a Standing Committee of the Board, called the Trustees Committee for APL, with responsibility to review the management and progress of the Laboratory and to insure that its efforts are devoted to missions of national importance which clearly are appropriate to its special competence. The Trustees Committee for the Applied Physics Laboratory meets with the management of the Laboratory several times a year, and at two meetings a year is joined by responsible senior representatives of the Department of the Navy. The present membership of this Committee is appended hereto. . . .

Because of questions recently raised in the Congress regarding Federal Contract Research Centers, the University wishes to reaffirm its position with respect to the place of the Laboratory in the University community. The relationship of the Applied Physics Laboratory with the other Divisions of the University is mutually beneficial and appropriate to the central purpose of the University. There is very significant interaction in both knowledge and professional staff, through joint appointments, through the Howard County branch of The Evening College, through collaboration with members of the School of Medicine in joint programs of biomedical engineering, and through direction of graduate students in systems engineering. Additional joint programs are being planned. The mutual goal of pushing forward science and technology, and a common desire for public service, provide a strong community of interest.

The top staff of the Laboratory is an outstanding and dedicated group of scientists which has remained together for over twenty years in large part because of the environment and support which The Johns Hopkins University has provided. We are convinced that the vitality and high standards of the Laboratory stem from this environment.

In summary, the President and the Board of Trustees of The Johns Hopkins University are convinced that the Applied Physics Laboratory has made and can continue to make highly significant contributions to the advancement of general science and technology, as well as to national security requirements, through its functioning as part of the University.

Approved by the Executive Committee,
Board of Trustees, The Johns Hopkins University,
January 8, 1968.

magnetic, and chemical. As a result, APL is recognized as a leader in the field of ocean physics.

One of APL's unique contributions to knowledge of the ocean has been in the conduct of large-scale ocean experiments. When dealing with phenomena extending tens or hundreds of miles, a very large experimental arena is required. To establish the characteristics of the complex and ever-changing ocean environment, an extended system of sensors—on ships and aircraft—is needed to obtain "ground truth." To validate the operational significance of the measurement, a submarine is required—a rare and precious asset. All of these must be tied together by communications, data reported to a central analysis station, and the whole tightly coordinated. The Laboratory has pioneered the organization and conduct of such tests on a scale an order of magnitude greater than previously attempted. The latest innovation has been the linking of ships with one another and with APL via satellite, making it possible for most of the scientists involved to remain at APL and make use of the full range of facilities. The results of these "big science-at-sea" experiments have been spectacularly successful in enabling decisive conclusions to be made in a matter of months rather than years (see Fig. 5).

In recent years, the expertise in undersea technology gained by APL extended the limits of APL's ability to contribute to a number of interesting and important civilian and military applications.

PERFECTING THE STRATEGIC DETERRENT

The original task of evaluating the operational fleet ballistic missile system never settled into a routine operation. On the contrary, the system was repeatedly extended in capability, notably the major changeover to the longer-range and multiple-warhead Poseidon and later

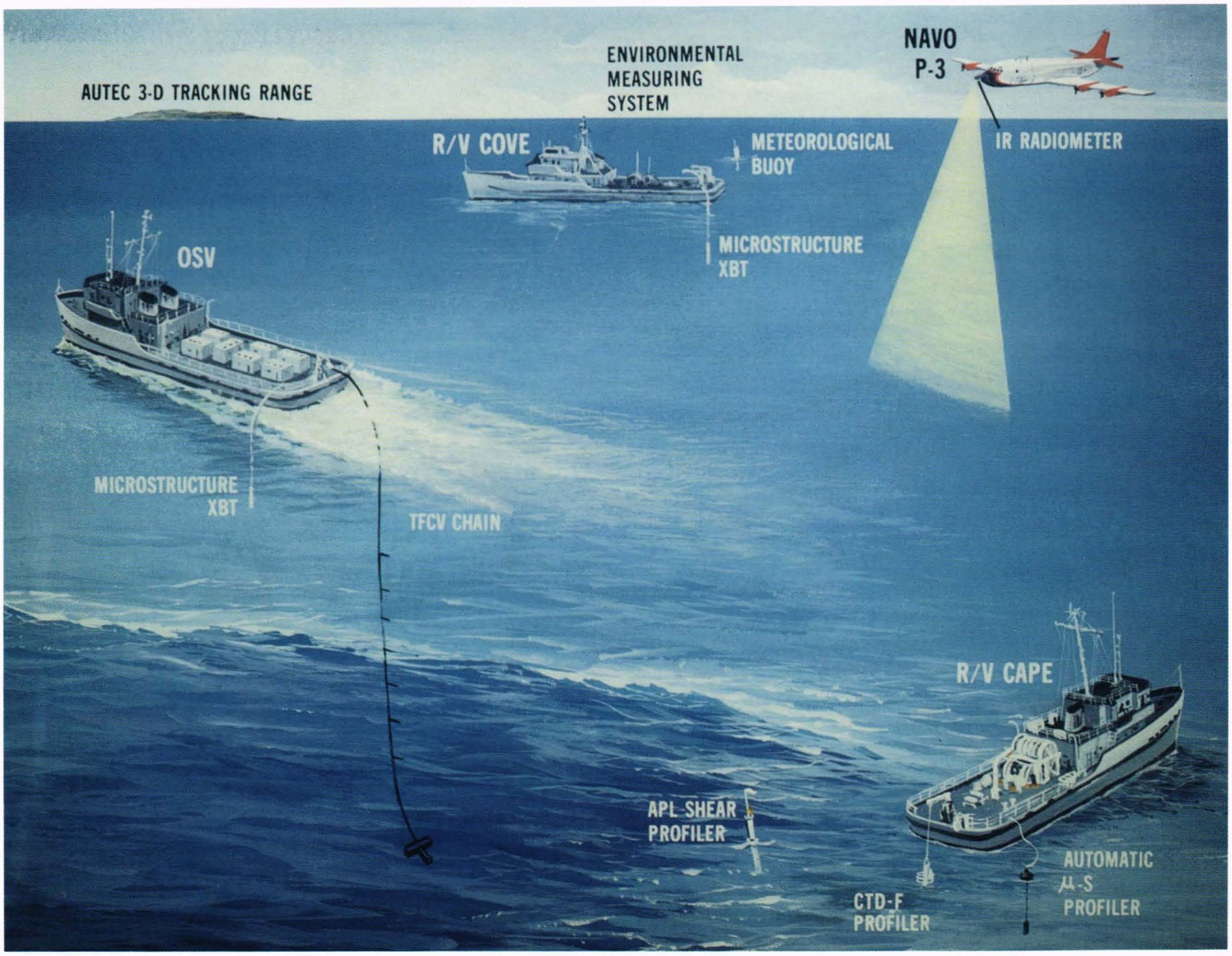


Figure 5. The SSBN security ocean experiment. The Laboratory has expanded the scale and scope of at-sea experimentation to areas covering a large swath of the ocean, with participation of a highly integrated group of submarines, surface ships, and aircraft, all equipped with hundreds of sensors. This enables the acquisition of scientific and operational data vital to submarine detection that had been impossible to obtain by previous methods.

the introduction of the Trident system. The evaluation task had to evolve correspondingly.

In the mid-70s, a new type of objective was introduced, that of achieving an order of magnitude improvement in accuracy, under the name Improved Accuracy Program. To accomplish this, it was necessary to identify and measure with great precision the different contributors to system aiming and firing errors, so that specific remedial actions could be taken. The Laboratory saw that this required that the missile be tracked with great accuracy throughout its flight, especially during powered flight and descent, which was beyond the capability of range radars. An original concept was devised to use satellite navigation, which had become very accurate, as the basis of measurement.

The technique was first demonstrated using the Transit navigation system and a special satellite, Transat, as a reference. Later, when the Global Positioning System (GPS) became fully operational, APL designed and built GPS receivers to be carried by Polaris test missiles. With tracking accuracies of a few feet, it has been possible to provide unequivocal answers to sources of system inaccuracy, with the result that current missile systems have shown terminal accuracies as good as the best land-launched ICBMs. This work has advanced the limits of missile accuracy manyfold from those considered practical in the immediate past (see Fig. 6).

Another new direction in the SSBN evaluation program has been the acquisition of sonar data on patrol. To determine if U.S. strategic submarines were being shadowed without their knowledge while on patrol, APL was asked to develop an on-board recorder that could store the signals received by the submarine's passive sonar for post-patrol analysis for any signs of other submarines. To record the required multiplicity of sonar channels at an adequate rate for the full patrol period, one needed a recorder with an order-of-magnitude greater speed and capacity than any in existence. A super recorder to meet this requirement was developed for APL by General Electric (then RCA), as part of the Submarine Patrol Analysis Recording System. Laboratory analysis of data obtained after several patrols revealed a number of submarine

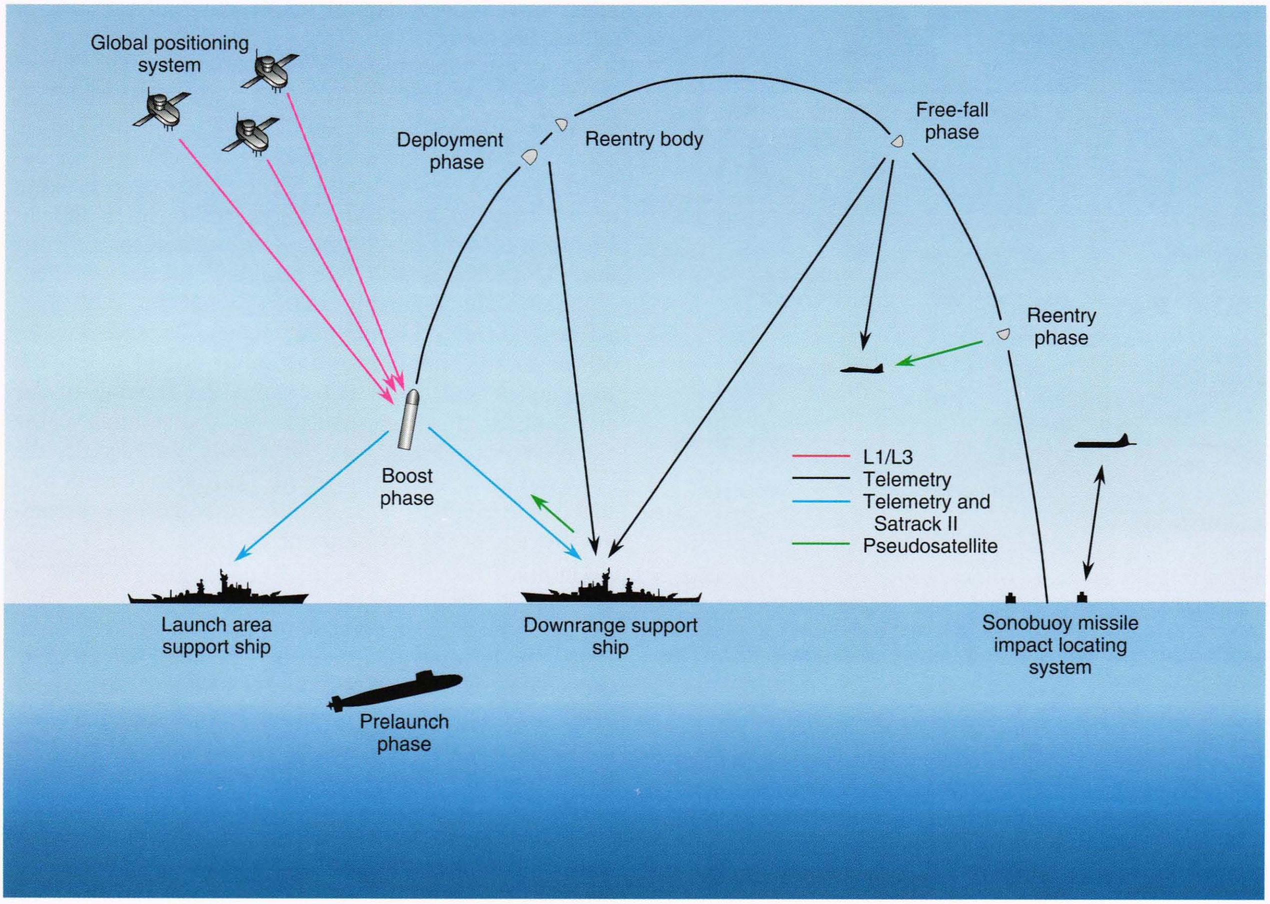


Figure 6. Improved accuracy instrumentation system. The world's most accurate ballistic missile tracking and impact location system, Satrack, uses the global positioning system for precision space tracking and submerged sonar sensors for impact location. It is designed to identify and measure all contributions to missile impact error.

trails not detected by the ship's sonar operators, providing a greatly extended submarine detection capability than existing SSBN sonar systems.

SCIENCE IN SPACE

Armed with the experience in the system engineering of guided missiles, the conquest of spacecraft technology proved readily achievable by APL engineers. As a result, APL was able to embark on a remarkably productive series of spacecraft developments for several applications. The APL spacecraft designs were characterized by innovative and elegantly simple approaches to stabilization, power, thermal control, electronic packaging, and other design features, together resulting in ultrareliable and low-cost spacecraft and space instruments. The spacecraft compiled an unmatched record of virtually flawless performance.

During the late 60s and 70s APL designed, built, and launched dozens of Earth-orbiting spacecraft carrying instruments designed to measure the Earth's geodetic and magnetic properties, as well as small astronomy satellites carrying ultraviolet, X-ray, and gamma-ray telescopes to observe the stars from beyond the atmosphere. Many of the instruments were built by other laboratories, including the first spaceborne X-ray telescope built by American Science and Engineering Company that had the distinction of making the first direct confirmation of a black hole.

The other major APL space undertaking in that period was the determination of the composition of charged particles around the planets and in interplanetary space. This was done by building particle detectors based on the principle of mass spectrometry, to be flown on interplanetary missions. The APL instrument package carried on both Voyagers consisted of an array of particle detectors capable of identifying electrons, protons, and atomic particles up to the mass of iron (see Fig. 7). The APL package, including the detectors and their associated control and processing devices, was as complicated as most entire APL-built spacecraft. Among the discoveries made by the particle detectors during the Voyager mission were measurements of extraordinarily high particle velocities in the plasmas orbiting around Jupiter and Saturn. For Saturn, the temperature corresponding to these velocities ranged up to a billion degrees Fahrenheit.

During the middle 1980s, APL was asked by the Kinetic Energy Weapons Office of the Strategic Defense Initiative (SDI) to undertake the technical direction of the first of what became a series of pioneering space experiments. The SDI program found the technology required to support the development of space-based antimissile weapons in the same embryonic state as that of guided missiles in

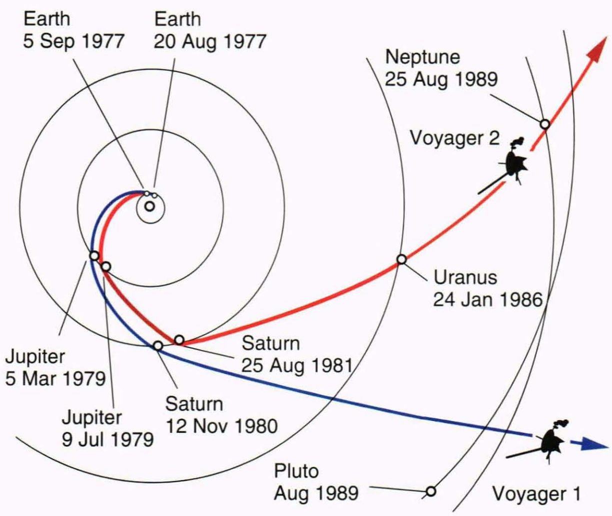


Figure 7. Particle physics in deep space. Space particle experiments by APL penetrate deep space aboard Voyager 1 and 2 spacecraft to map the composition and distribution of energetic particles surrounding the outer planets, their satellites, and in free space.

the 1940s. A highly expedited theoretical and experimental program was mounted to establish a body of knowledge on which system concepts could be based; the urgency stemmed from the fact that without such information, other elements of the program could not proceed.

The challenge given to APL was to conceive, organize, and direct within one year a project leading to a realistic space intercept—an impossible schedule. Given the priority associated with the SDI program and a wide latitude in the manner of execution, this was exactly the kind of undertaking that APL had a unique talent to conduct. A system concept, necessarily based on adapting existing components, was quickly agreed on, a highly skilled contractor team was assembled, and an organization similar to the Bumblebee pattern was set up. The experiment resulted in an in-orbit intercept of two launch rockets, using a converted air-to-air missile for guidance, all monitored by sensitive, state-of-the-art instruments integrated into a "science package" by APL. It was completed fifteen months after program start and was successful in every respect.

The other projects in the series are further space experiments to determine how missiles in space appear to a wide spectrum of space sensors—an essential piece of knowledge for designing weapons to intercept attacking missiles before they enter the atmosphere. This is another example of expanding the limits of knowledge in an area critical to national security.

STRETCHING THE LIMITS OF FLIGHT

The successful development of the ramjet from an unproven concept to a reliable high-performance engine for the Talos missile established a solid empirical basis for designing ramjet engines. During that period, APL with its associate contractors pioneered in research on combustion and the fluid dynamics of ramjet inlets, directed toward providing the theoretical underpinning for ramjet technology.

Notwithstanding the progress made in rocket performance during the 50s and 60s, jet engines retained their advantage for sustained flight through the atmosphere for extended ranges. The efficiency of conventional jet engines falls off rapidly above Mach 3, however, because of the extreme temperatures that result when the air stream is slowed to subsonic speeds after entering the inlet. This effect appeared to be a fundamental boundary of the favorable regime for ramjet propulsion. With characteristic disregard for arbitrary limits, APL undertook to design a ramjet combustor that could sustain supersonic combustion and hence not require the slowing of the incoming air stream to subsonic speeds. Building on the extensive knowledge base previously established, the limit was successfully breached. The development of a supersonic combustion ramjet, or scramjet, was a landmark event in the evolution of jet propulsion.

During the 1970s, APL was the principal preserver of interest and knowledge in hypersonic ramjets and further advanced the understanding of the technology. In the mid-1980s, the government established an ambitious program to develop a demonstration model of a National AeroSpace Plane (NASP) that would be "a vision of the ultimate airplane, one capable of flying at 17,000 miles an hour, 25 times the speed of sound . . . that can routinely fly from Earth to space and back, from conventional airfields, in affordable ways . . . a revolutionary technical, managerial and programmatic concept." The primary propulsion system for the NASP, from Mach 3 to nearly orbital speeds, will be a supersonic combustion (or scramjet) engine. As a key participant in the consortium of government, university, and industrial organizations, APL is making a decisive contribution to this far-reaching initiative.

THE FLEET AS A FIGHTING UNIT

Throughout the period of expanding Laboratory missions into space, under the sea, and in nondefense applications, APL's dedication to fleet defense never diminished. As noted earlier, however, its focus expanded from the fuze to the missile to the guidance radar and then to the total ship combat system, including the critical surveillance systems, keeping pace with the evolution of the threat and the growing importance of countering "surprise, confusion, and saturation." In the 80s, APL expanded its activities beyond the combat system of a single ship to encompass an entire task group.

The impetus for the expansion came from two sources. First, the growing air threat was cutting into the effectiveness of a single ship to defend itself, let alone nearby high-value ships. Second, the introduction of Aegis ships into the fleet provided sources of high-quality air pictures resistant to enemy electronic countermeasures. If the air pictures could be conveyed in useful form to other ships in the battle group and their weapons employed in coordinated fashion, the total effectiveness could be multiplied severalfold.

To exploit the potential gains of such tactics, APL was designated technical director in 1978 for the battle group antiair warfare coordination effort by the Aegis Program

Office. Since then, a systematic program has been under way to bring the concept to fruition (see Fig. 8).

An essential prerequisite step was to provide all ships in the force with automatic detection and track capability, which was accomplished by applying SYS-1 technology. Next, an automatic intership location (gridlocking) system was developed that received track data from neighboring ships and derived a common reference by identifying and aligning corresponding tracks. With this foundation, an Aegis ship can supply all ships in the force with its air picture in a manner aligned with its own weapon coordinate system.

In recent years, the Navy has been putting into place the elements required to support battle group coordination. Nearly all combatants have been or are being equipped with automated detection and tracking and gridlock systems based on APL developments. Sea trials have demonstrated the effectiveness of coordinated tactics.

In the meantime, APL efforts have moved into an even higher level of antiair warfare operations: command support, which addresses the difficult challenge of providing operational commanders with the tactical information they need in a form most easily comprehended. The work exploits the recent advances in computer graphics and display technology to produce tactically significant images of the operational environment. A key to the process is a correlator/tracker that correlates all incoming data to produce a "highest probability" track picture containing the most reliable estimates of the situation.

As with other APL developments, the command support effort is predicated on at-sea experiments in real operational environments to assure relevance to the Navy's *real* problems. The work is expected to continue in the years ahead.

The sinking of the Israeli destroyer *Elath* in 1967 by an Egyptian cruise missile fired from a patrol boat impelled the Navy to create a strike missile capability of its own. The result was development of the Harpoon and Tomahawk cruise missiles, which have become the surface and submarine fleet's primary offensive armament. The Laboratory has played a key role in both programs, especially in the crucial guidance area where it has expanded the limits of accuracy for this type of weapon. The spectacular success of the pinpoint cruise missile strikes during Desert Storm was in no small measure due to APL contributions in the laboratory and support in the field.

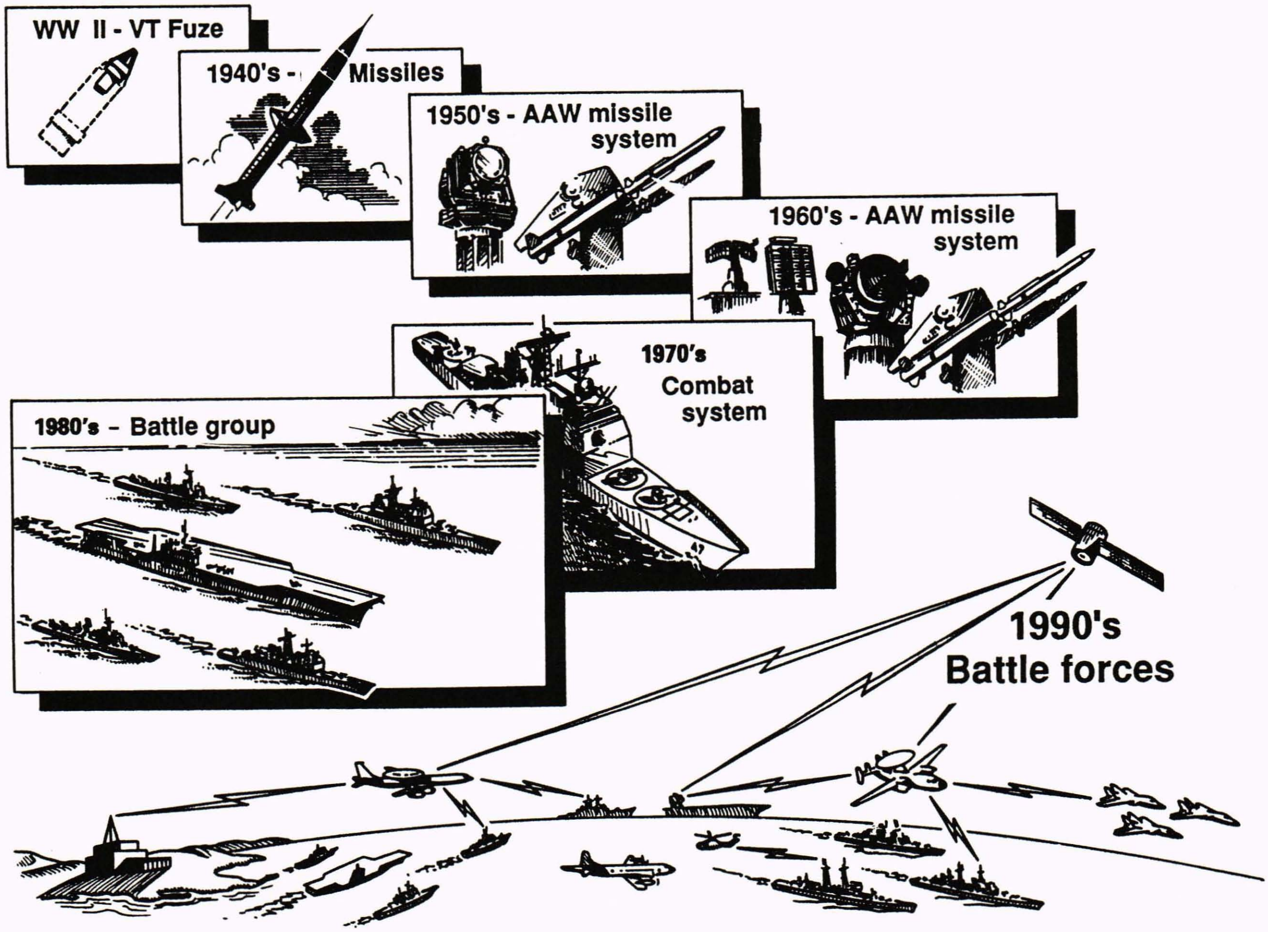


Figure 8. The Laboratory has enabled the Navy to expand the scale of coordinated engagement to an entire battle group by gridlocking all the ships' surveillance and weapon control systems, linking them with secure communications, and automating detection and track and identification of enemy forces, thus greatly increasing the combat effectiveness of the battle group.

CONTRIBUTING TO THE PUBLIC WELFARE

In the early 1960s, APL's interest in contributing its expertise to the solution of important problems in the civilian sector was in tune with the prevailing national sentiment and was encouraged by Defense Department policy statements. In the ensuing years, the Laboratory has actively sought nondefense areas to which the special talents of its staff could make a particularly effective contribution. The results have been rewarding to the staff and valuable to the public.

Perhaps the most notable and enduring of these initiatives has been the collaborative biomedical program with the world-famous Johns Hopkins Medical Institutions (JHMI). The program began in 1965 through the initiative of the Chairman of the APL Research Center working with key members of the School of Medicine. A series of exploratory meetings was held with a number of top medical researchers and key APL scientists and engineers to explore areas of medical diagnosis and treatment that could benefit from advanced technical instrumentation or analysis. Initial interest centered around cardiology, ophthalmology, and neurology. After selecting a significant problem, a team consisting of a JHMI physician and an APL engineer or scientist pursued each problem in a close collaborative relationship. Each team member worked on a part-time basis to enable him to continue his regular duties. The formula has worked extremely well, and the program grew to involve as many as a hundred active APL and JHMI collaborators.

The broad scope of this fruitful collaboration may be inferred from just a few of its more than 100 products. One was the use of an argon laser to coagulate blood vessels that can proliferate through the retina, especially in diabetic patients. A device was developed in the late 1960s that can be focused through a standard ophthalmic instrument, a technique now widely accepted. Another example was a series of delicate instrumented probes for detecting neural responses in the brain that has extended the understanding of the mechanism of eye–hand coordination in primates. A third is the development of an automated clinical information system that now serves the Johns Hopkins Hospital's general outpatient clinic, emergency room, and Oncology Center. A fourth is a series of implantable devices based on the application of space technology, including a rechargeable heart pacemaker, a medication system for diabetics, and a cardiac defibrillator to save high-risk patients. The APL/Johns Hopkins collaborative biomedical engineering program remains a unique partnership today.

An entirely different area has been that of renewable energy. Even before the oil crisis of 1973, brainstorming sessions were held to consider how APL's talents might be applied to develop alternative energy sources. The method selected was ocean thermal energy conversion, in which warm surface ocean water in tropical regions is used to vaporize ammonia to drive a turbine generator (see Fig. 9). The ammonia is condensed by cold water drawn from a depth of several thousand feet. This renewable energy source was predicted to be able to produce power at competitive prices with fossil fuels if developed to its full commercial potential. Initially, APL work to demonstrate the practicality of the concept was supported by the Department of Energy, but in the 80s that Department adopted the policy that costs of further development should be borne by industry. The drastic drop in the price of oil after the oil crisis ended led industry to conclude that the risk of full-scale development was too great without some assurance of federal support. Despite marginal support, limited effort continued at APL to provide advice and assistance to interested municipalities and contractors and to fully document its technical and economic basis. A definitive treatise on the subject is being published.

Other APL initiatives in the public sector included providing technical support to the Urban Mass Transportation Administration in the development of automated transit concepts, development of a harbor traffic control system for San Francisco based on the technology developed for Navy automatic detection and tracking, investigation of clear air turbulence and weather radar for the Federal Aviation Administration, participation in a nationwide research effort to understand the physical causes and medical consequences of fires and the development of useful tools for the Fire Service, and the provision of analytical support to the State of Maryland Power Plant siting program.

The Laboratory's entry into the field of graduate education started as a means of helping staff members earn advanced degrees after-hours. Courses leading to a Master of Science degree in Electrical Engineering were first taught at APL in 1964 under the academic sponsorship of The Johns Hopkins University Evening College. So many APL staff members enjoyed teaching as a change from their defense work that the program was expanded to include Applied Mathematics, Computer Science, Space Technology, and Applied Physics.

In 1980, an entirely new program leading to a Master of Science degree in Technical Management was established at the request of the President of the University. The program was directed toward providing an educational basis for the increasingly important tasks of managing high-technology projects and organizations. In 1985, the important component of system engineering was added to the program. Not duplicated on any other campus, the program owes its existence to the unique characteristics of APL as part of Johns Hopkins.

Because of the high quality of the faculty, applicants to the APL "campus" came from the local community and beyond, swelling the number of students to more than 2000 in the 1980s. In 1983, APL's educational program was transferred to the academic sponsorship of the Johns Hopkins G.W.C. Whiting School of Engineering; today, the program is the largest part-time graduate engineering program in the country. The Laboratory is the only large university laboratory engaged in graduate education on a comparable scale. This has been an especially successful example of collaboration between APL and the University's academic divisions (see Fig. 10).

The expansion of the limits of APL's mission beyond that of national security to other important problems affecting the public welfare has been strongly encouraged

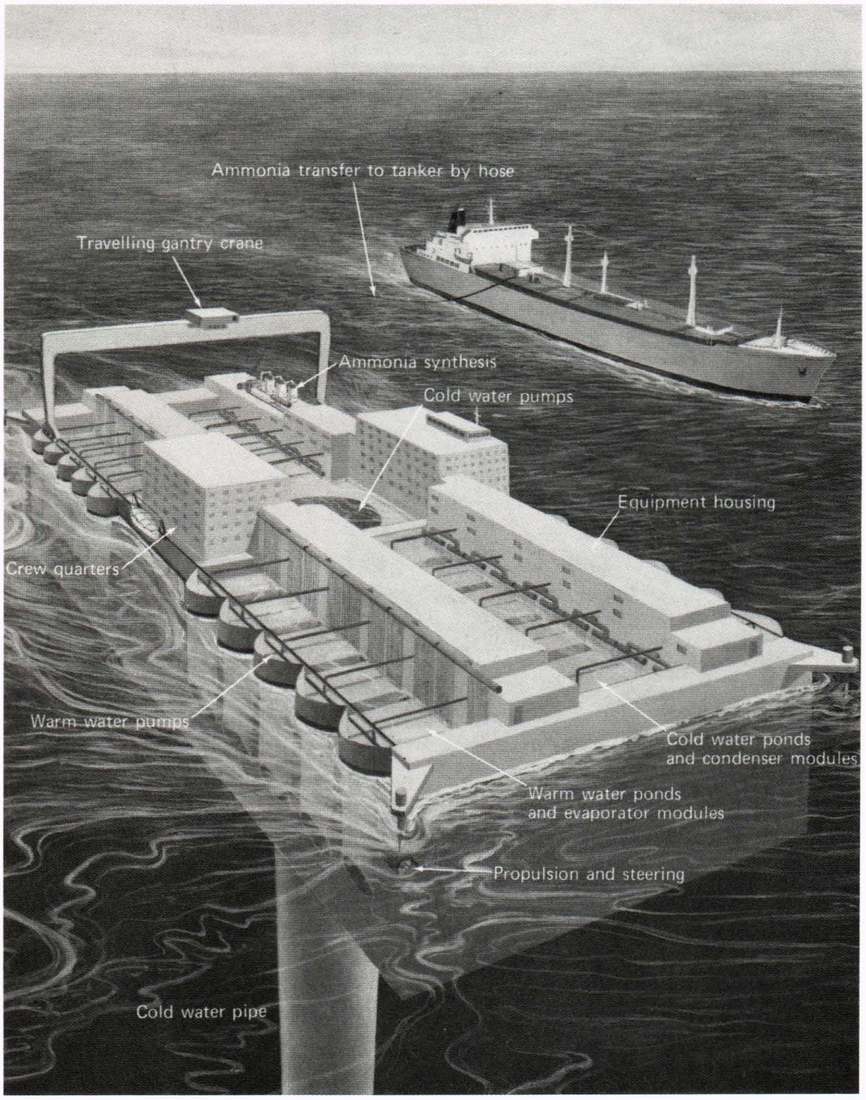


Figure 9. Ocean thermal energy conversion plant ship concept, as devised by APL, offers one of the very few long-term solutions to the energy-dependence problems of the United States and other nations. Its technical and economic feasibility have been demonstrated so that industry can proceed to implement it, given sufficient economic incentives.

by the University President and Trustees and has materially enhanced APL's reputation both within and outside the University.

THE NEXT FIFTY YEARS

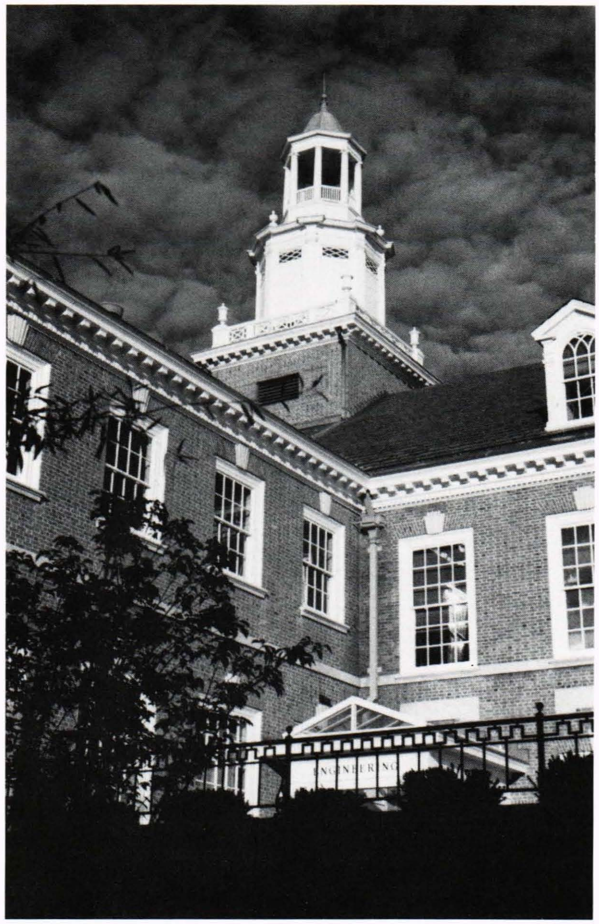
The past fifty years have seen many changes in the world, but none has been more profound than those of the past several years. It is not an exaggeration to say that today's world is changed in fundamental ways from yesterday's, with new sets of problems and the need for new priorities. These changes have already led to a rethinking of this country's needs, especially those relating to national security. They will challenge the Laboratory in many ways, and its best talents and experience will be called on to respond.

Without minimizing the fundamental changes that have occurred, it is important also to maintain a sense of balance based on the lessons of history. The disintegration of communism as a commanding force, and with it the Soviet bloc, has reduced the threat of Armageddon, but it has not eliminated political struggle and potential conflagrations. We learned from the recent Gulf War how our world can be threatened by a single adversary. The experience has also taught us how decisive high technology has become in warfare. It was the complete control of information, weapons with literally pinpoint accuracy, and an unprecedented degree of coordination that combined to overwhelm an enemy with formidable conventional armament.

The victory in the Gulf could not have been achieved without the military preparedness of the U.S. forces and our government's readiness to lead a United Nations–backed effort to expel the invader. As long as international lawlessness remains a threat, one of this country's roles in the world may well be the occasional wielding of military power in defense of victims of aggression in parts of the world critical to our national interest.

In meeting future U.S. security needs, except during actual conflict, the Navy is certain to remain the prime means of projecting power abroad. As combat systems become still more sophisticated, the need for integrating the decision and weapons control functions—areas in which APL is currently a leader—will become even more important. The Laboratory's system and operational orientation makes it unique among organizations available

G.W.C. Whiting
School of Engineering



Computer Sciences
Electrical Engineering
Applied Physics
Applied Mathematics
Technical Management

APL Education Center
(1736 students)

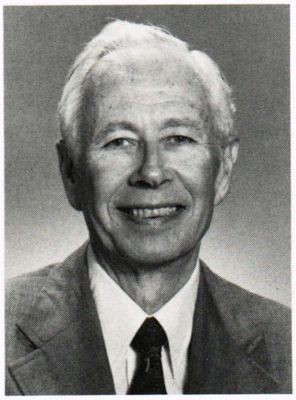
JHU Montgomery Center
(446 students)

Figure 10. The graduate engineering education program at Johns Hopkins/APL, the largest in the United States and taught under the auspices of the G.W.C. Whiting School of Engineering at the APL Education Center and the JHU Montgomery Center. The faculty is drawn largely from APL. (Top photograph by Jeremy Green. Lower right photograph by Curtis Martin.)

to the Navy in welding together the great variety of subsystems and equipment that must operate as highly integrated components in the fleet.

Opportunities for APL to contribute to future national needs are by no means confined to security; the apparent reduction in the immediate foreign threat will focus public attention on national problems previously given low priority. Efforts will be made to increase U.S. productivity and competitiveness, preserve the environment, decrease the costs of medical care while improving its quality, decrease our dependence on foreign oil, maintain air safety in the face of multiplying traffic, devise new forms of mass transit, maintain security in the increasingly complex computer-based services, and solve countless other problems of our society. There will be no dearth of potential problems to solve as long as APL maintains its traditional character of expanding the limits that stand in the way of highly desirable goals.

THE AUTHOR



ALEXANDER KOSSIAKOFF received a B.S. degree in chemistry from the California Institute of Technology in 1936 and a Ph.D. from The Johns Hopkins University in 1938. He taught at the Catholic University of America (1939–42), served with the wartime Office of Scientific Research and Development, and was Deputy Director of Research at the Allegany Ballistics Laboratory, Cumberland, Maryland, from 1944 to 1946.

Dr. Kossiakoff joined APL in 1946 and served as head of the Bumblebee Launching Group until 1948, when he was appointed Assistant Director. He became Associate Director in 1961 and was appointed Director in 1969. In 1980, he stepped down as Director and was appointed Chief Scientist, a position he currently occupies. He is also Program Chair of the Master of Science Program in Technical Management at the G.W.C. Whiting School of Engineering.

In recognition of his work on national defense during World War II and at APL, Dr. Kossiakoff was awarded the Presidential Certificate of Merit, the Navy's Distinguished Public Service Award, and the Department of Defense Medal of Distinguished Public Service. He is a Fellow of the American Institute of Chemists and a member of the American Association for the Advancement of Science, the Cosmos Club, and the Governor's Scientific Advisory Council.