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THE STRATEGIC MISSILE SUBMARINE FORCE AND APL'S ROLE IN ITS DEVELOPMENT

The U.S. Navy's Fleet Ballistic Missile program is one of the largest, most successful weapons systems development programs in our country's history. In the thirty-seven–year span of this program, three generations of increasingly capable weapons systems (Polaris, Poseidon, and Trident) have been developed and deployed. Contributions to these systems have spawned three of the technical departments at the Applied Physics Laboratory: Space, Strategic Systems, and Submarine Technology.

INTRODUCTION

The U.S. Navy's Fleet Ballistic Missile (FBM) program, begun in 1955, is recognized today as the cornerstone of the U.S. nuclear strategic deterrent. The submarine-launched ballistic missile (SLBM) and its nuclear-powered submarine launching platform, the SSBN (submersible ship, ballistic, nuclear), provide a mobile, stealthy, long–patrol-duration weapon system with enormous retaliation potential. This system provides a significant deterrent advantage over land-based missiles or aircraft systems because of its mobility and its ability to avoid detection in vast ocean patrol areas, thus remaining invulnerable to a surprise attack. The Navy's Strategic Systems Program (SSP), formerly the Special Projects Office (SPO) and the Strategic Systems Program Office (SSPO), has overseen the development and operational deployment of three generations of increasingly capable weapon systems (Polaris, Poseidon, and Trident), with six variants of the SLBM (Figs. 1 and 2). The success of this program is largely due to the uniqueness of the SSP organization itself, the vision and drive of its early leaders, and the dedication of the many contractors who contributed to the system's birth and evolution.

Figure 1. A Trident II (D5) submarine-launched ballistic missile (SLBM) is launched off the coast of Florida. The D-5 missile is the latest addition to the U.S. Navy's strategic deterrent arsenal.

After World War II, long-range ballistic missile development in the United States proceeded somewhat slowly until the mid-1950s. Intercontinental Ballistic Missile (ICBM) concepts with ranges in excess of 5000 miles were studied as early as 1946, but it was generally accepted that such designs would have to await technology advances in rocket propulsion as well as guidance and warhead technologies to be feasible.[1] Nuclear warhead technology was in its infancy, and the atomic bombs of the day were large and heavy.[2] Meanwhile, the United States favored the smaller air-breathing, winged cruise missiles as long-range surface-to-surface attack weapons. Both the U.S. Air Force and Navy developed and deployed several generations of early cruise missiles. The Navy's first nuclear-armed, operational, submarine-based strategic missile was Regulus I (Fig. 3).

By the end of 1954, the Eisenhower administration had accorded ballistic missile development the highest national priority.[1] A political decision was made, however, to limit research and development to four programs: a primary design and a backup design for both an ICBM and an intermediate range ballistic missile (IRBM).[3] At this time no consensus existed within the Navy to embark on a Navy ballistic missile (later known as the Fleet Ballistic Missile). Some concern had been expressed that such a program might become too large, thus endangering other traditional programs and career paths. This lack of consensus, compounded by in-fighting among the Bureau of Aeronautics (BuAer), the Bureau of Ordnance (BuOrd), and the Naval Research Laboratory (NRL) over who should have development responsibility[3] for the ballistic missile, lost the Navy its early opportunity for a leading role in U.S. ballistic missile development. By early 1955, the U.S. government had assigned responsibility for development of the primary ICBM (Atlas), the no. 2 ICBM (Titan), and the primary IRBM (Thor) to the U.S. Air Force,[3] leaving only the no. 2 IRBM program open for competition between the

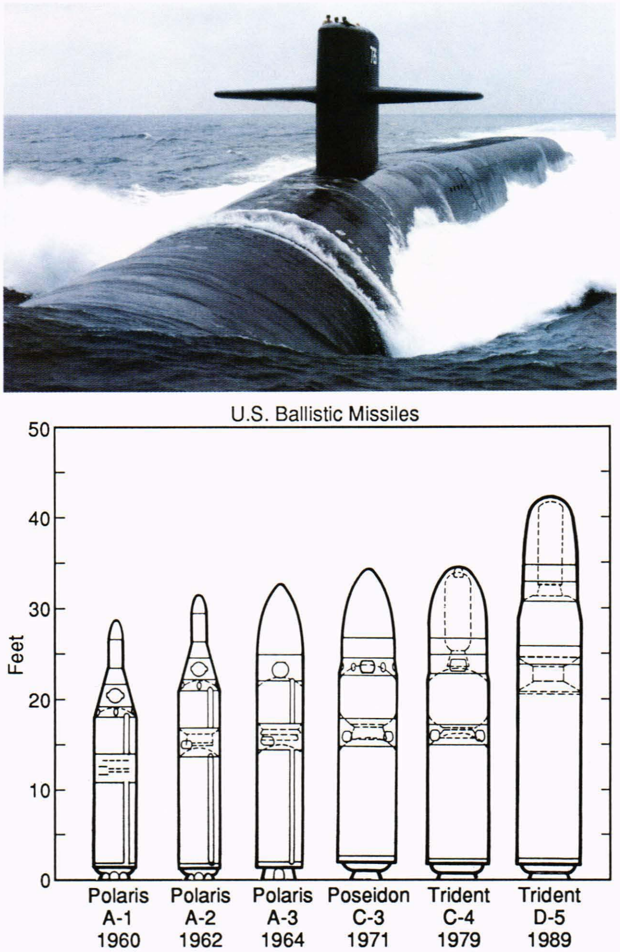

Figure 2. An Ohio-class Trident submarine at sea. The Trident submarines are replacing the older Polaris submarines, which are nearing the end of their useful service life. The lower graphic shows the evolution of the six submarine-launched ballistic missile (SLBM) variants.

Figure 3. The Regulus I missile, shown here preparing for a test launch from the USS *Tunny* (SSG 282), was the Navy's first operational strategic missile. The Regulus Attack Missile system was declared operational in 1954. The Regulus fleet was projected to grow to fourteen SSG's; however, only five were built because the program was canceled in 1958 in favor of Polaris.

Army and the Navy. The Army's missile program was subsequently judged to be the more experienced, and it was selected for the no. 2 IRBM (Jupiter).

Admiral Arleigh Burke, appointed Chief of Naval Operations in August 1955, played a pivotal role in saving the FBM concept.[3] He forged a consensus within the Navy to seek an FBM capability, while continuing the naval cruise missile developments, and engineered a joint effort with the Army to design a Navy version of the liquid-propellant Jupiter for shipboard basing (aboard converted Mariner-class cargo ships).[3] Although this concept generated little enthusiasm, the Navy recognized that the joint program was necessary for it to pursue its long-range goal of a solid-propellant, submarine-based FBM.

On 8 November 1955, the Secretary of Defense directed the Army and Navy to proceed jointly with development of IRBM no. 2 (Jupiter) with maximum urgency.[4] A month earlier, NRL had been given the responsibility of developing the Vanguard missile to place a small satellite into Earth orbit as part of the U.S. contribution to the International Geophysical Year (1957–1958), leaving the feuding BuAer and BuOrd organizations as the remaining candidates for FBM program manager. In what was to become perhaps the most important decision affecting the ultimate success of the FBM program, the Navy decided to select neither, but to create an entirely new organization. On 17 November 1955, the Secretary of the Navy created the Special Projects Office (SPO) to handle the unique problems related to the ship-based version of the Jupiter IRBM.[4] A second important decision was selecting Admiral Raborn, an aviator who had served in the BuOrd, as the first director of the SPO. This decision was not only a brilliant compromise to secure the continued cooperation of the BuAer and BuOrd, but it also placed a man of great vision and drive at the helm of a unique new organization within the Navy.[3]

THE SPECIAL PROJECTS OFFICE

The initial concept for the SPO organization was that it be small, with an initial personnel authorization of only forty-five officers and forty-five civilians; it was to rely on the bureaus for technical support and would be disbanded upon completion of the FBM development phase.[3] In early 1956, SPO encouraged a design study between Aerojet General Corporation and the newly formed Lockheed Missiles and Space Division; the result was a solid-propellant version of the Army/Navy Jupiter, referred to as the Jupiter S (Fig. 4).[3] Its huge size (44 ft long, 120-in. diameter, 160,000 lb), however, meant that only four such missiles could be deployed aboard a large submarine, rendering it impractical. Significant reductions in warhead and missile weight and an increase in solid-propellant specific impulse were still needed. Captain (later Admiral) Levering Smith was recruited to SPO in 1956 and set about investigating an improved, lighter-weight solid-propellant FBM design. Captain Smith had considerable experience in solid-rocket development from prior assignments at the Naval Ordnance Test Station, Inyokern, California, and White Sands, New Mexico,[5] where he had responsibility for naval missile test programs.

A breakthrough in high-impulse, solid-propellant technology was demonstrated in a small-scale test motor firing by Atlantic Research Corporation of Alexandria, Virginia, in January 1956.[6] Large amounts of powdered aluminum were added to the basic motor propellent ingredients (plasticized polyvinylchloride and ammonium perchlorate). The SPO needed confirmation that this discovery could be practical in a larger-size motor and requested in late January 1956 that Aerojet undertake this task. Aerojet

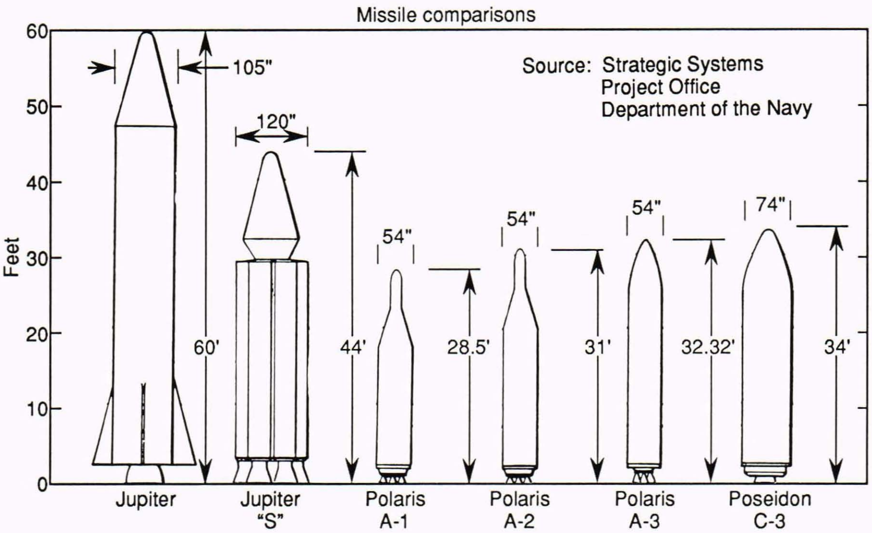

Figure 4. Early design concepts for the Navy's Fleet Ballistic Missile Program. The figure clearly illustrates the dramatic improvement achieved with Polaris over the joint Army/Navy liquid-propellant Jupiter and solid-propellant Jupiter S designs.

subsequently produced the world's first successful large-scale (which at that time meant greater than a 20-in. diameter) high-impulse, solid-propellant rocket motor.[5] In addition to implementing the Atlantic Research propellant technology, Aerojet had to overcome the problem of propellant cracking during the curing process, a problem that plagued the larger solid motors of that era.

In the summer of 1956, an extremely fortuitous event for the FBM Program occurred. At the request of the Chief of Naval Operations, the National Academy of Sciences Committee on Undersea Warfare convened a summer study at Nobska Point, Woods Hole, Massachusetts, to analyze the Russian submarine threat.[3] At this conference, committee members became aware of SPO's concept (wish, actually) for a smaller, lighter-weight version of the solid-propellant FBM and were convinced that a nuclear submarine fleet armed with such a missile would be far more effective than the Jupiter system the Navy was currently committed to build. The eminent Dr. Edward Teller, the father of the H-bomb, attended the conference and contributed the stunning news that low-weight, significant-yield thermonuclear warheads compact enough for use in torpedoes should be available by the end of the decade.[3] By projecting realistic technology advances, the Nobska Point Panel on Strategic Uses of the Underseas recommended that the Navy build a submarine-based missile having a weight of eight to fifteen tons, and a range of 1000 to 1500 miles with a low-weight, low-yield warhead.[3]

The FBM concept embedded in the Nobska Point Panel report was endorsed by the SPO and the Chief of Naval Operations. An Atomic Energy Commission study in September 1956 confirmed Dr. Teller's estimates that a suitable small, lightweight warhead could be developed by the early 1960s.[3,5] This knowledge, combined with projections of success for the new high-impulse solid propellant, convinced Admiral Raborn to seek approval to drop the Jupiter development in favor of the new solid FBM missile concept, which he named Polaris.[5] The Secretary of the Navy, convinced of the value of the new solid-propellant Polaris, prepared a study for the Secretary of Defense showing the cost savings of substituting Polaris for Jupiter S. On 8 December 1956, the Secretary of Defense authorized the Navy to proceed with Polaris and to terminate its joint participation with the Army's Jupiter program.[4] On 19 December 1956, the Secretary of the Navy reaffirmed that Polaris would have highest priority, and he assigned responsibility for development of the entire system to the SPO.

By early 1957, the SPO had organized the Special Steering Group (later to become known as the Steering Task Group)[3] to define the basic design envelope and parameters for the FBM and its nuclear submarine platform. The initial target concept was for a contingent of three to six submarines, each housing sixteen missiles with a range of 1500 nautical miles (later to become the Polaris A-2 missile design). The missile was to be ready for testing no later than 1 January 1963, and a submerged submarine launch capability was to be operational in 1965.[3] These plans changed dramatically with the launch of Sputnik I by the Soviet Union.

THE IMPACT OF SPUTNIK

No single event has had such a stunning impact on the technological destiny of our country as the launch of the world's first artificial Earth satellite, Sputnik I, by the Soviet Union on 4 October 1957. Sputnik I was the equivalent of a technological Pearl Harbor. It was followed quickly by the successful orbiting of the larger, more sophisticated Sputnik II, which contained the dog named Laika, only a month later on 3 November 1957. The impact of these dramatic early Russian space successes was amplified by the highly publicized initial launch failures of the prototype Vanguard missile (6 December 1957, 5 February 1958, and 28 April 1958) slated to launch the first U.S. Earth satellite. By early 1958, American technical prowess had slumped, and the concept of a technological missile gap had been firmly implanted in the public consciousness.[7] Initial concern over the status of the missile and space programs quickly grew to anxiety requiring decisive action. The U.S. government accelerated the military ballistic missile programs and began to overhaul the aeronautics and space programs, leading to the formation of the National Aeronautics and Space Administration (NASA).

By 22 October 1957, the Secretary of the Navy had proposed an acceleration in the Polaris FBM program to the Secretary of the Defense.[3] The accelerated program had three new milestones: (1) development of a new interim missile with a shorter range (1200 miles), launchable from land or sea by December 1959 (this design would become the first Polaris missile, the A-1); (2) initial operational capability for two FBM submarines by early 1962, followed by a third within three months; and (3) attainment of the original 1500-mile missile (eventually to become the Polaris A-2 missile) by mid-1963, two years earlier than originally planned.[3,4] This plan was approved by the Secretary of Defense on 9 December 1957, and the SPO advanced the already lively pace of the FBM program to that of a wartime development.

Because the accelerated schedule did not allow time to design a new SSBN, the first three SSBN's were converted from existing Skipjack-class nuclear attack submarines (SSN's) under construction by cutting them in half and inserting a new 130-foot section housing sixteen missile tubes. The first SSBN, the USS *George Washington* (SSBN 598), was converted from what had been planned to be the USS *Scorpion* (SSN 598). The USS *George Washington*, commissioned on 30 December 1959, conducted the first two historic submerged launches of Polaris (A-1 missile) on 20 July 1960.[4]

An ironic footnote to the impact of Sputnik on the Polaris FBM program and APL is worthy of mention. The ascendancy of Polaris to the Navy's highest priority and the accelerated development resulting from Sputnik's launch caused a funding dilemma within the Navy that resulted in cancellation of three major programs in 1957–1958: the Seamaster jet seaplane, the Regulus II missile, and APL's Triton missile.[3] Cancellation of Triton was a great disappointment.[8] Nonetheless, the launch of Sputnik presented APL's Dr. F. T. McClure the opportunity to recognize that the Doppler shift from its crude radio transmitter could be used to determine a satellite's precise orbit, prompting the brilliant concept for a satellite-based navigation system (eventually to become Transit). This concept would solve what had been one of the greatest technical obstacles to the Polaris FBM concept, that is, the ability to correct (via satellite information updates), and therefore limit, the size of submarine navigation errors while on extended patrols. Funding for the development of Transit at APL was the origin for what has grown into the many-faceted APL Space Department.

POLARIS

The Applied Physics Laboratory's earliest involvement in the Polaris FBM program grew from its reputation in missile system development (Talos, Terrier, Triton) and, in particular, its background in solid-propellant motor technology.[8,9] R. E. Gibson (APL Director), A. Kossiakoff (Assistant Director), and W. H. Avery (Bumblebee Project) had all come to the Laboratory from Allegany Ballistics Laboratory, which had carried out wartime developments of solid-rocket weapons. In 1956 Kossiakoff chaired, and Avery was a member of, the Polaris Ad Hoc Group[8] formed by the Department of Defense at Admiral Raborn's urging to investigate the technical problems in developing a solid-propellant FBM. Captain Levering Smith, newly arrived within the SPO, was actively seeking a small solid-propellant FBM design. Admiral Raborn requested that APL provide a technical consultant to Captain Smith, and this task was assigned to R. B. Kershner (Supervisor, Terrier Program). By 1957 APL was involved in a variety of studies spanning such activities as solid-rocket handling safety, theoretical and experimental investigations into solid-propellant resonant burning problems, a review of early Polaris performance specifications and test plans, electronics packaging, rotatable rocket nozzles, and inflight staging techniques. By November 1957, a small group had been formed under Kershner to begin a dedicated involvement in Polaris. On 1 December 1957, because of the accelerated Polaris development schedule caused by the launch of Sputnik, the APL Director, at the request of the Navy, asked that Kershner devote full-time participation to this program.

By early 1958, the interest in space flight and exploration had grown so that a Space Exploration Advisory Panel headed by F. T. McClure was formed at APL on 21 February to advise the Director. In his famous 18 March 1958 memorandum to Gibson, McClure outlined his ideas for a satellite Doppler navigation system; these ideas had resulted from observing Sputnik. In a companion memo on 18 March 1958, McClure reported: "On 17 March I also went over the proposal with Dr. Kershner, who was quite excited about the application to the Polaris system. I believe he is to have a first-round discussion with Captain Levering Smith today with the idea of getting immediate Polaris support to carry out some early investigations . . . with the idea of making a full-fledged proposal by April 1 if the initial studies look promising" (APL internal memo, 18 March 1958). These studies ultimately led to the revolutionary Navy Navigation Satellite System (also called Transit), which would achieve worldwide acclaim for APL.[10,11]

On 21 July 1958, APL announced the formation of the Polaris Division, headed by Kershner, noting that ". . . the principal responsibility of the Laboratory under this task is the planning and conduct of the BuOrd evaluation of the Polaris system . . . . In addition, the Laboratory has undertaken the development of an entirely new method of locating the position of an object on the Earth's surface, which has particular and immediate application to the Polaris program" (APL internal memo, 21 July 1958). The new Polaris Division consisted of three groups: Polaris Analysis and Performance, headed by R. C. Morton; Polaris Evaluation and Test, headed by R. K. Dahlstrom; and Satellite Navigation Development, headed by R. B. Kershner. The latter activity, initially funded through SPO, was the seed that would later grow into a much larger and broader activity in space research and exploration at APL.

The first navigation satellite, Transit I, was launched on 1 September 1959, but it failed to achieve orbit. Enough data were obtained, however, during its 25-min flight to verify the practicality of the satellite navigation concept, and continued development was authorized. In January 1960, APL announced formation of the Space Development Division (later to become the Space Development Department), under Kershner, to concentrate on Transit development. By 1963 Polaris evaluation activity was consolidated into the Polaris Division Central Office under R. C. Morton, which in 1973 became the Strategic Systems Division and in 1975 the Strategic Systems Department. What had begun in 1958 as a modest evaluation effort grew into an APL department of approximately 400 people over the next several decades and would spawn a third department, the Submarine Technology Department, in the 1970s.

Figure 5 is a diagram of the early structure of the family of organizations that the SPO assembled to design, build, and maintain Polaris. The Applied Physics Laboratory is shown twice, depicting both the navigation satellite development and the systems evaluation and analysis functions it undertook for Polaris. It is amazing that the Polaris weapon system was developed without a prime contractor. Because of this unusual approach, an activity with a "systems perspective" was needed, that is, a technically competent agency that understood both detailed subsystem performance as well as its impact on the larger system. Admiral Rayborn wanted objectivity, independence, and expertise in an area in which few weapons development organizations had experience at that time; he wanted a complete "systems approach." He also recognized the importance of testing to the success of a deployed weapon system. It is reported that Admiral Raborn did not want to be remembered for developing and deploying a fleet of submarines filled with "telephone poles."[3] The Polaris missile and its weapon system would be instrumented and tested in a comprehensive evaluation program. The task of planning and executing this evaluation program went to APL at the Navy's request.

In 1958 APL assisted Captain Levering Smith, who by then was the SPO Technical Director, in preparing the first Polaris evaluation program (the SPO Technical and Operational Evaluation Program), which combined what had been separate technical and operational test requirements. The accelerated schedule resulted in little opportunity for subsystem acceptance testing. The Laboratory recommended an initial shipyard-installation test program to verify integrated subsystem performance on each new SSBN. The continuing effort would be a two-phase test program conducted by Navy crews rather than by technical contractors, under conditions approximating those encountered on a tactical patrol. The first phase would consist of a predeployment test (Demonstration and Shakedown Operation, DASO) of each FBM submarine at Cape Canaveral, Florida, to include the firing of a test missile to certify the combined performance of the integrated weapon system and crew. The second phase would occur approximately a year after SSBN deployment and would consist of a periodic random selection of an SSBN from the deployed fleet, conversion of several deployed missiles to a test configuration, and conduct of a launch operation, including use of tactical communications assets. Originally called Operational Tests, these are now called Commander in Chief Evaluation Tests, or CET's. The CET's allow current, representative performance of

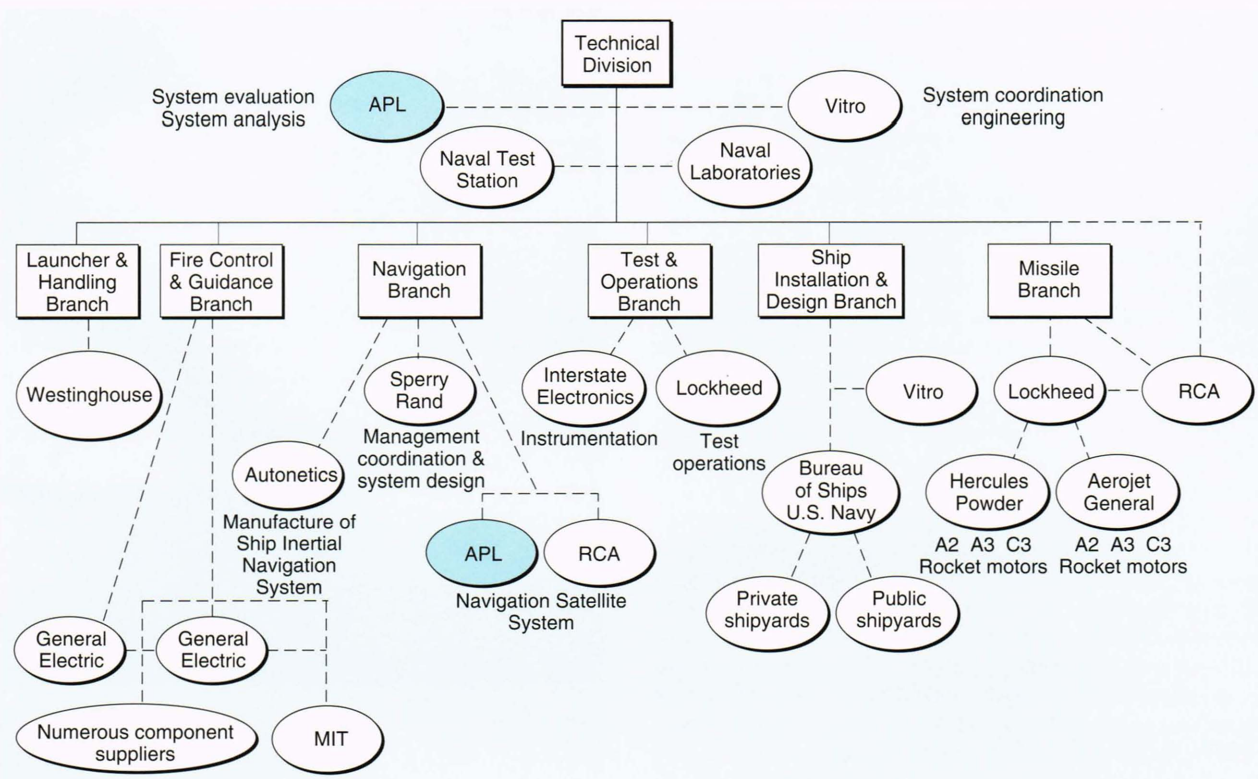

Figure 5. Major contractor network for the Fleet Ballistic Missile Program. (Reprinted, with permission, from Ref. 3.)

the deployed FBM fleet to be monitored via demonstrated results throughout the life of the weapon system.

Significant technical problems were encountered with the early Polaris AX series of developmental flight tests (not uncommon for missiles systems being developed at that time).[5] The first Polaris AX-1 pad launch occurred on 24 September 1958, but it failed in flight. It was followed by four successive failures. The Laboratory's active participation in analyzing these early flight problems began with the AX-3 flight in December 1958 at SPO's request.[9] Finally, on 20 April 1959, the first completely successful flight (AX-6) was achieved. The early Polaris AX flights were conducted with a simple trajectory sequencer, and it was not until the AX-11 flight on 15 July 1959 that a successful inertially guided Polaris missile flight occurred. The Polaris development effort culminated with the historic successful launches of two Polaris A-1 missiles from the USS *George Washington* (SSBN 598) on 20 July 1960. Laboratory staff members participated in the onboard technical review of subsystem performance, which resulted in approval to conduct the launches.[9,11] Lieutenant L. P. Montanaro, the Navy's Test Engineer for these historic launches, later joined APL, became head of the Strategic Systems Department, and eventually rose to the position of Assistant Director for Program Development. Kershner and Dahlstrom later received the Distinguished Public Service Award, the highest Navy recognition for a citizen not an employee of the Department of Defense, for their contributions to the success of the first historic Polaris submarine launches. In addition, APL was awarded the Navy Certificate of Merit, granted only for the most outstanding contributions and achievements, for its role in planning and maintaining a comprehensive program for FBM system development analysis. The citation stated that "APL contributed immeasurably in achieving the first successful firing of the Polaris missile from a submerged submarine."[12] Other staff members received Navy Certificates of Commendation for their work on Polaris.

On 15 November 1960, the USS *George Washington* deployed on the first historic FBM deterrent patrol with a full complement of A-1 missiles. Subsequent Polaris SSBN's encountered new technical problems while on patrol. In 1961 SPO expanded APL's role by requesting assistance in operational patrol evaluations.[9] Patrol data requirements were defined and instrumentation concepts developed, leading to the first generation of Patrol Operational Readiness Instrumentation. The first full tactical FBM patrol analysis by APL began in 1962. The Applied Physics Laboratory introduced the Weapon System Readiness Test (WSRT) concept, which uses a simulated launch message sent to an unalerted SSBN on patrol, causing it to prepare for a simulated missile firing. In addition to providing realistic training, the WSRT affords a demonstration of reaction time and provides instrumented subsystem performance in a tactically realistic environment. Magnetic tapes and other data are assembled into patrol packages and returned to APL for processing, evaluation, and distribution to other agencies.

In 1962 the only complete end-to-end test of a U.S. nuclear-armed ballistic missile was conducted with Polaris. On 6 May 1962, the USS *Ethan Allen* (SSBN 608) conducted a submerged launch of the Polaris A1 tactical missile to a target area near Christmas Island in the Pacific Ocean, including successful detonation of its thermonuclear warhead (Operation Frigate Bird, Fig. 6).[4]

EVOLUTION OF THE SUBMARINE-LAUNCHED BALLISTIC MISSILE

Congress, along with the new Kennedy administration, continued to support the FBM program, and the fleet of Polaris SSBN's rapidly grew to forty-one deployed submarines by 1967.[4] Each of these SSBN's carried sixteen SLBM's. Deployment of this formidable strategic fleet posed a particularly difficult challenge for the Soviet defense establishment, because at the time the Soviets had no effective defense against ballistic missiles and only limited antisubmarine warfare (ASW) capability. The Polaris threat caused the Soviets to redirect their priority naval developments[13] to focus on ASW and likely contributed to their decision to build and deploy a limited antiballistic missile (ABM) system.

The evolution of strategic missiles in the Soviet Union proceeded along considerably different paths from that of the United States.[14] The bulk of the Soviet strategic forces would eventually become deployed as land-based systems. It was not until the 1960s that the Soviets began to expand their sea-based ballistic missile program with a sense of urgency similar to that of the United States. Unlike the United States, most Soviet SLBM develop-

Figure 6. Confirmation of a successful end-to-end flight test of Polaris (Operation Frigate Bird, 6 May 1962). The mushroom cloud from the Polaris warhead detonation is viewed through the periscope of a submarine in the vicinity of the target. This is the only complete test of a U.S. nuclear ballistic missile weapon.

ments resulted in liquid-propellant systems. The role of the submarine as a strategic weapon seems to have been overlooked initially by the Soviets; early Soviet SLBM designs and missions were apparently aimed more at strike and antinaval force roles.[13] This latter role is worthy of special mention. There is reason to believe that the original requirement for the Yankee-class SSBN was to defend against Western sea-based nuclear forces. The Soviets attempted to develop a naval tactical ballistic missile (SS-NX-13) for the Yankee SSBN, which ". . . with a 400-mile range and a terminal guidance system, would have been suitable for use against Western carrier task forces and possibly even Polaris submarines."[13] The SS-NX-13 was never fully developed because of technical problems. In 1961 Soviet planners redirected their SLBM developments toward a more strategic mission to match the U.S. SSBN buildup. Figure 7 compares the buildup and the composition of both the U.S. and U.S.S.R. SSBN fleets.[15] Table 1 summarizes the characteristics of these fleets.

The capabilities of the U.S. and U.S.S.R. SSBN fleets have changed considerably with time, not only because of the number of SSBN's deployed, but also because of the different capabilities and the mix of the many SLBM variants carried by these submarines. The United States has developed and deployed six SLBM variants, the Soviet Union almost twice as many.[14,16] Each new U.S. SLBM variant was developed with a specific improvement or new capability intended to offset or complicate potential Soviet attempts to counter this force. This strategy forced the Soviets to devote an ever-increasing amount of their military resources to address the U.S. FBM threat, diluting other efforts.

The first U.S. SLBM, the Polaris A-1 missile, was actually an interim missile derived from the original design (later to be known as the Polaris A-2). As previously discussed, this interim missile had a shorter range and resulted from an acceleration to the Polaris program caused by Sputnik. The first real variant to Polaris was the A-3 missile, which included the use of three multiple-reentry vehicles for improved damage effectiveness and almost doubled the range of the A-2 missile (1500 nm) to 2500 nm. The added missile range meant that SSBN's deployed with A-3 could patrol at greater distances from the U.S.S.R. in a much greater region of the ocean, dramatically complicating the ASW mission for the Soviets. The next U.S. SLBM variant, the Poseidon C-3 missile, was the world's first Multiple Independently Targetable Reentry Vehicle (MIRV) weapon system. Up to fourteen reentry vehicles could be carried on a maneuverable stage, called a bus, and could be deployed on targets separated by large distances on the ground. This MIRV capability was intended to overwhelm any Soviet ABM system that might be widely deployed, but its ability to attack many more targets also added a significant leverage to the FBM fleet. The next-generation U.S. SLBM, the Trident I (C-4) missile, again increased range (to 4000 nm)[5] to complicate the ASW problem and improve SSBN survivability, while also demonstrating technology enhancements to improve accuracy (stellar-aided guidance) and payload. The latest U.S. SLBM, the Trident II (D-5) missile, is the first U.S. SLBM to have a high-accuracy goal and is specifically designed to take full advantage of the larger launch tubes aboard the new Ohio-class Trident submarines. The increased range, accuracy, and payload of the D-5 missile make it a true sea-based mobile ICBM, which is among the most accurate and versatile missiles in the U.S. strategic arsenal.

Each Ohio-class Trident SSBN carries twenty-four SLBM's. At present, eighteen Trident SSBN's are planned, eight currently configured to carry the Trident I (C4) missile; and the remaining ten (if all are procured) will be configured for the Trident II (D5) missile. The option exists to backfit the first eight Trident SSBN's to carry D5. The newer Ohio-class Trident SSBN's are replacing the older, original Polaris SSBN's, which are approaching the end of their useful life. Decommissioning the older U.S. and Soviet SSBN's is being coordinated with new SSBN deployments to maintain compliance with treaty limitations.

Other than the United States and the Soviet Union, only the United Kingdom, France, and the People's Republic of China have developed an SSBN weapon system.

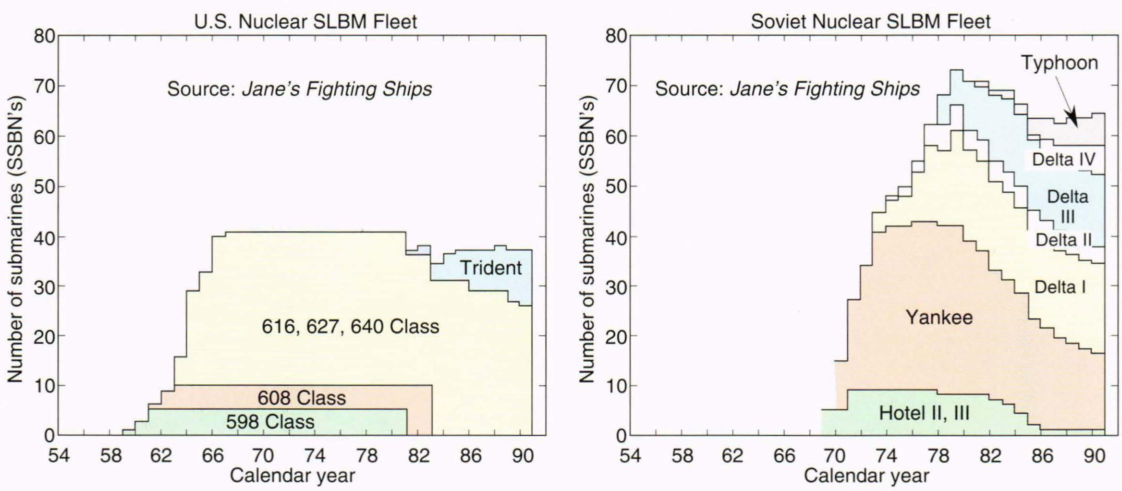

Figure 7. Evolution and composition of the U.S. and U.S.S.R. submersible ship, ballistic, nuclear (SSBN) fleets. SLBM = submarine-launched ballistic missile.

Table 1. Characteristics of SLBM submarines. (Source: *Jane's Fighting Ships.*)

SSBN (number)	Submerged displacement (tons)	Length (ft)	Beam (ft)	Submerged speed (kt)	Launch tubes	Missile (SLBM)
United States						
598 Class (5)[a]	6,700	382	33	30	16	Polaris A1
						Polaris A3
608 Class (5)[a]	7,900	410	33	30	16	Polaris A2
						Polaris A3
616 Class (9)	8,260	425	33	25	16	Polaris A2
						Polaris A3
						Poseidon C3
627 Class (10)	8,240	425	33	25	16	Polaris A3
						Poseidon C3
						Trident I-C4
640 Class (12)	8,250	425	33	25	16	Polaris A3
						Poseidon C3
						Trident I-C4
726 Class (11+)	18,700	560	42	20+	24	Trident I-C4
(Trident)						Trident II-D5
Soviet Union						
Hotel II (8)	6,350	426	30	25	3	SS-N-5
III (1)					6	SS-N-8 (Mod 1,2)
Yankee I (33)	9,450	427	38	27	16	SS-N-6 (Mod 1,3)
II (1)					12	SS-N-17
Delta I (19)	10,200	450	39	25	12	SS-N-8 (Mod 1,2)
II (5)	11,300	508	39	25	16	SS-N-8 (Mod 1,2)
III(14)	11,700	524	39	24	16	SS-N-18 (Mod 1,2,3)
IV(6+)	12,150	545	39	24	16	SS-N-23
Typhoon (6+)	26,500	563	81	?	20	SS-N-20

Note: SLBM is a submarine-launched ballistic missile, and SSBN is a submersible ship, ballistic, nuclear.
[a]Retired from strategic service.

In late 1962, the United States and the United Kingdom reached a joint agreement that resulted in the U.K. Polaris Program.[4] Under that agreement, the United States agreed to sell the United Kingdom Polaris A-3 missiles and the SSBN subsystem equipments that formed the Polaris weapon system; the United Kingdom would build its own nuclear warheads for the missiles as well as four U.K. Polaris SSBN's. The first U.K. SSBN, HMS *Resolution*, was launched in September 1966, participated in a Demonstration and Shakedown Operation (DASO) at Cape Canaveral, Florida, in early 1968, and was operational soon thereafter. The SSP and APL support U.K. personnel in planning and evaluating the U.K. DASO's. The United Kingdom embarked on an upgraded reentry system for their Polaris A-3 missiles in 1977, referred to as Chevaline (A-3TK).[17] A decision was made in 1980 to modernize the U.K. SSBN fleet by building a new class of SSBN capable of carrying the U.S.-built Trident II (D-5) missile.

THE APPLIED PHYSICS LABORATORY'S CONTRIBUTIONS

Since its initial involvement in 1958, the APL Polaris Division, now the Strategic Systems Department (SSD), has continued to perform its traditional test planning, execution, and evaluation tasks for each new FBM weapon system. These activities include specifying evaluation criteria and data requirements, proposing instrumentation concepts, developing analysis methodologies and software, and conducting flight test mission planning. The SSD staff routinely supports SSP in the conduct of DASO evaluations of SSBN's at Cape Canaveral, Florida. A permanent APL Field Office has been operated by SSD at this site since 1962. The DASO provides a valuable opportunity for firsthand interaction with SSBN subsystem hardware, instrumentation systems, and crews. The SSD staff actively participates in resolving technical problems aboard individual SSBN's, as well as making significant recommendations for fleetwide material and procedural improvements. Individual evaluation reports are prepared for SSBN's conducting DASO's, CET's, and selected tactical patrols. These unit evaluations provide the basic data source for a cumulative systems evaluation and characterization of the deployed fleet. A detailed weapon system performance evaluation report (CINCEVAL report) is prepared for the U.S. Commanders in Chief of the Atlantic and Pacific Forces and forwarded to the Joint

Chiefs of Staff annually. The CINCEVAL report provides current planning factors (e.g., description of deployed force, reaction time, reliability, accuracy, etc.) needed for the strategic targeting process (Fig. 8).

By the early 1960s, at the request of both Navy and non-Navy sponsors, APL's evaluation tasks began to expand beyond that of the Polaris weapon subsystems. Figure 9 provides a chronology of the evolution of the major programs within SSD. Over the decades, APL staff members have participated in many panels, engineering studies, and special tests aimed at resolving problems or providing long-term improvements to the FBM weapons systems. Some of APL's activities are noteworthy as improvements to the FBM weapon system or because they were the origin for growth into other program areas.

In 1959 APL scientists were recognized by the Navy for a major technological breakthrough, the concept of a movable (rotatable) nozzle for thrust vector control of solid-propellant rocket motors.[17] Early Polaris missiles (A1 and A2) had used fixed motor nozzles with jetevators, that is, molybdenum rings mounted on pinions, which were rotated into the rocket motor exhaust flow to develop control forces. The rotatable nozzle concept greatly improved the efficiency and reliability of later Polaris missiles. More importantly, it made possible the development and use of more powerful solid propellants, with higher exhaust gas temperature and flow rates, for application to future missile and space rockets.

In early 1963, APL undertook an effort to resolve major performance deficiencies in the SSBN hovering control system, a system necessary to maintain ships' attitude and depth control at the near-zero speeds required for missile launch. The early SSBN hovering control systems implemented a pneumatic controller that exhibited a variety of problems. The Laboratory built an exact replica of the controller and tested it in a ship-motion simulator, resulting in discovery of an SSBN roll-coupling phenomenon. A modification to the controller was designed at APL to optimize performance and was successfully demonstrated on board an SSBN at DASO. A ship alteration (SHIPALT) design change was approved by the Navy, and SHIPALT kits were manufactured at APL and shipped to the deployed fleet. A parallel effort led to an APL design for an improved, solid-state electronic controller, which became the standard for present-day hovering controllers.

Another effort, which later grew into a major program area, began somewhat inconspicuously in 1963. The Navy requested that APL review problems with the SSBN MK 113 torpedo fire-control system, a natural extension of ongoing analysis as the Polaris fire-control computer was shared with the MK 113. Early efforts uncovered significant deficiencies in the MK 113, but also highlighted shortcomings in sonar equipments. The poor passive-bearing performance of the SSBN sonars contributed significantly to MK 113 target solution errors. The MK 113 work led to a small APL project to improve SSBN defensive capabilities by developing an active sonar signal intercept receiver. As concerns over Soviet ASW capabilities became heightened in the early 1970s, the early APL sonar project blossomed into a larger activity, the SSBN Security Technology Program, which addressed a variety of technical issues related to SSBN detectability and subsequently expanded into oceanography and ASW activities. The SSBN Security Technology Program effort eventually became the third APL technical department to evolve from the Polaris program: the Submarine Technology Department.

In 1972 the Navy requested APL to design a test program for an independent analysis and evaluation of sonar equipments unique to SSBN's. This program, the Sonar Evaluation Program (SEP), was structured on experience gained

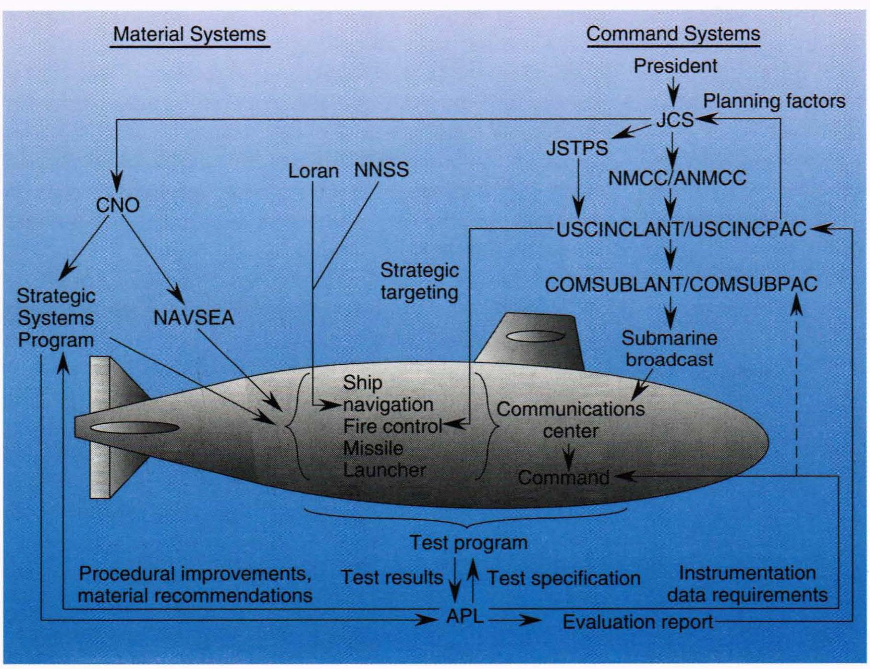

Figure 8. Dual feedback paths for APL test and evaluation results: material and procedural improvements and planning factors for strategic targeting. CNO = Chief of Naval Operations; JCS = Joint Chiefs of Staff; JSTPS = Joint Strategic Target Planning Staff; NMCC = National Military Command Center; ANMCC = Airborne NMCC; USCINCLANT = U.S. Commander in Chief, Atlantic Forces; USCINCPAC = Commander in Chief, Pacific Forces; COMSUBLANT = Commander, Submarine Forces, Atlantic; COMSUBPAC = Commander, Submarine Forces, Pacific; NAVSEA = Naval Sea Systems Command; NNSS = Navy Navigation Satellite System.

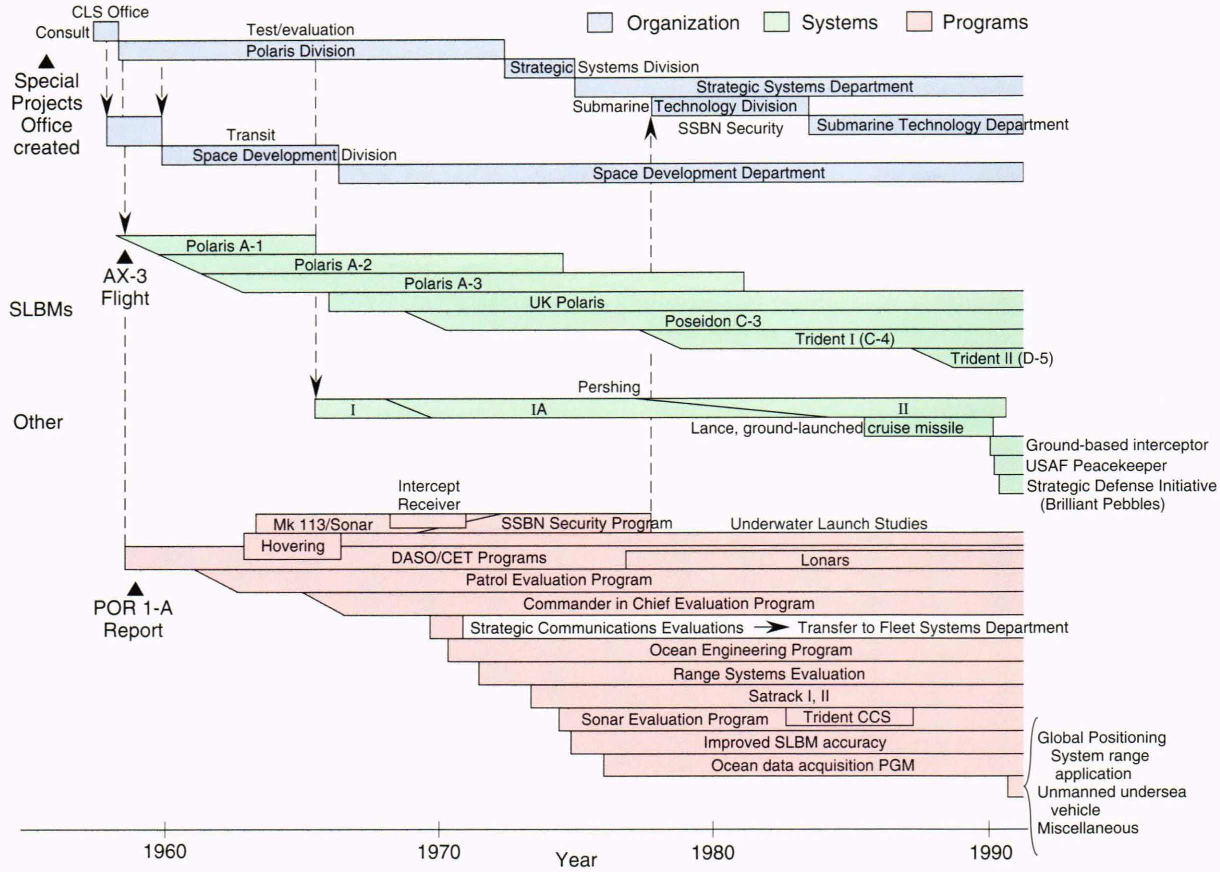

Figure 9. Evolution of Strategic Systems Department programs. SSBN = submersible ship, ballistic, nuclear; SLBM = submarine-launched ballistic missile; DASO/CET = Demonstration and Shakedown Operation/Commander in Chief Evaluation Test.

in the FBM weapon system evaluation program and consisted of (1) a controlled at-sea sonar test during DASO and (2) an operational evaluation using sonar data collected on tactical SSBN patrols. A decision was made to record data from the complete hydrophone (sonar sensor) array during an entire SSBN patrol, allowing postpatrol processing of sonar contact data for comparison with patrol perceptions from limited real-time displays. The task posed a monumental data recording and processing problem on a scale not previously attempted. The Laboratory and its subcontractors developed a state-of-the-art SEP Acoustic Recording System (SPARS) for installation onboard SSBN's and an SEP Analysis System (SPAN). Analysis of SPARS-equipped SSBN patrols has continued since the initial patrol evaluation in 1979 and has expanded to include limited SSN patrol evaluations. The SSD has made significant contributions to acoustic data recording and signal processing technologies, resulting in improved submarine sonar performance and use. Current activities include research into automated acoustic detection and classification and improved sonar data display technology.

An evaluation program for the range safety and instrumentation systems aboard the USNS *Range Sentinel* was begun at the Navy's request in 1971. The Poseidon CET program called for ripple launchings, which meant that multiple missiles had to be acquired and tracked by the *Range Sentinel* for launch area telemetry reception and range safety. A sophisticated antenna management system existed aboard the *Range Sentinel,* and the Navy was concerned about its ability to support the CET. The SSD participated in the test and the evaluation of this system to validate its performance. This activity has grown into a continuing effort that includes such activities as evaluations of National Test Range assets needed to support SLBM testing, new launch area selection studies, the development of cost-effective ocean-bottom sensor array survey and maintenance concepts, and upgraded instrumentation capabilities. Real-time missile tracking concepts for range safety using Global Positioning System (GPS) satellites were developed and implemented at the Atlantic and Pacific national test ranges to support C4 and D5 missile testing.

In the early 1970s, the Navy initiated a series of efforts to improve the understanding of SLBM accuracy error sources and to identify options for implementing quantifiable accuracy improvements in future generations of SLBM's. The SSD participated in several special investigations and analytical studies that improved insight into SLBM accuracy. In 1974 the Navy consolidated its SLBM accuracy investigations into a formal accuracy technology effort called the Improved Accuracy Program, with the primary objective of establishing development options for the Trident II (D5 missile) weapon system and the infrastructure needed to validate, through "precise tests and measurements," that such a system could achieve its high accuracy goals. The SSD has participated actively in the improved SLBM accuracy effort and has made numerous important contributions. Among these was the development of a novel satellite tracking (Satrack) system for precision trajectory error analysis using GPS satellites (Fig. 10). A unique missile-borne translator was designed at APL to receive and shift the GPS signals to S-band frequency and to amplify and transmit them to receiving stations on the ground. A very large (more than 200 states) Kalman-filter postflight processor was developed to combine the GPS data, missile telemetry, and detailed error models for trajectory/guidance system error estimation. Because it provided acceptable real-time solutions for range safety as well as high-rate data for postflight precision trajectory estimation, Satrack was ideally suited for the increasingly longer-range FBM test missiles.

The Satrack development was a joint activity between APL's Space Department and SSD. The first-generation Satrack I system was initially tested during a Trident I (C4) missile flight test in 1978. In 1979 SSP initiated APL's effort into an Accuracy Evaluation Study to identify testing, processing, and instrumentation requirements (Fig. 11) needed for evaluation of the improved-accuracy Trident II (D5) missile. This study established the basis for development of Satrack II, which is currently in use. The Satrack I and II hardware and software developments and the many years of practical experience in conducting analyses with these systems has established APL as a leader in the field of GPS applications and has led to requests for APL involvement in other missile and space programs of national importance. The Satrack/GPS has been adapted to the test and evaluation of the Army Exoatmospheric Reentry-Vehicle Interceptor System, the Strategic Defense Initiative Brilliant Pebbles System, and USAF Peacekeeper missile flight tests.

Each new generation of SLBM has been more capable and complex than its predecessor. The flight test telemetry systems added to these SLBM's have also become more extensive, more complex, and of increasingly higher data rates. New instrumentation systems have been added to the weapon system as program evaluation requirements have evolved, leading to a dramatic increase in the volume and type of electronic data recorded throughout the life of the FBM program. As a result, the Navy has funded SSD to develop and maintain an increasingly capable FBM data processing and evaluation facility. The SSD also has developed and operates a variety of other dedicated instrumentation or data processing facilities in support of commitments to other programs.

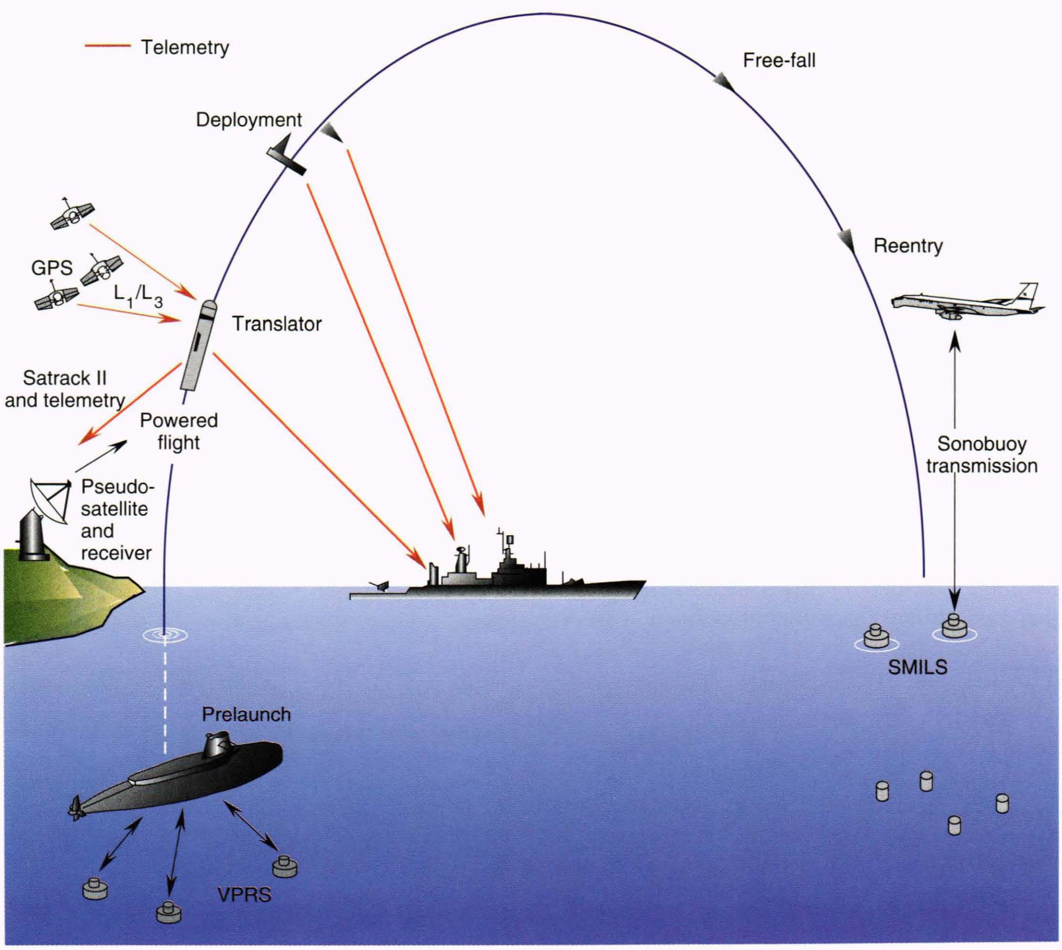

Figure 10. Satellite tracking (Satrack) system for precision SLBM trajectory/guidance error analysis. GPS = Global Positioning System; SMILS = Sonobouy Missile Impact Location System; VPRS = Velocity and Position Reference System.

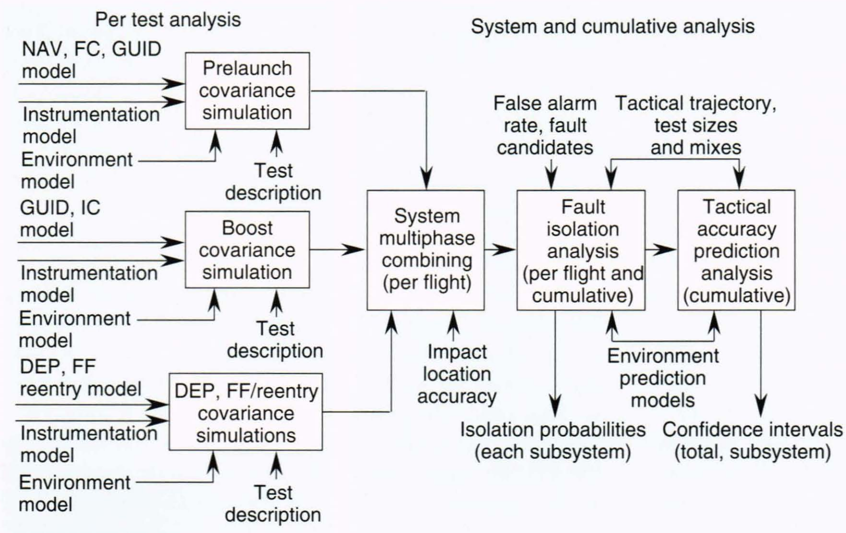

Figure 11. Flow diagram for instrumentation requirements and weapon system accuracy trade-off studies. NAV = Navigation Subsystem; FC = Fire Control Subsystem; GUID = Guidance Subsystem; IC = initial conditions, DEP = deployment; FF = free flight.

One non-FBM SSD program is deserving of special recognition: the U.S. Army Pershing Weapon System evaluation effort. In 1964 the U.S. Army began to deploy its first-generation nuclear-armed mobile Pershing I in Europe. Based on APL's reputation, and in particular its recognized contributions to the Polaris Program, APL was requested by the Office of the Deputy Director of Defense Research and Engineering to assist the Army in designing, conducting, and evaluating an Operational Test Program for Pershing. The Applied Physics Laboratory accepted this task on 26 November 1965 and assigned the effort to the Polaris Division. From 1966 through 1990, SSD performed the same functions for the Army's Pershing Program Manager that it was performing for the Navy. In 1987 the United States and the Soviet Union signed the Intermediate-Range Nuclear Forces Treaty, which included provisions for the elimination of the U.S. Pershing weapon system. Shortly thereafter, a programmed drawdown of Pershing units from Europe began. In September 1990, SSD closed its European Field Office, culminating 24 years of continuous service to the U.S. Army in Europe. The contributions of the SSD staff to the highly successful Pershing program are many and varied. It is only fitting that this article end with a final hail and farewell to Pershing and the family of dedicated government, civilian, and military personnel that made it work.

THE FUTURE

Dramatic changes have been unfolding around the world in recent years. These changes have had a profound impact on Eastern Europe and the Soviet Union in particular. The welcome easing of tensions between the superpowers holds promise for the future. A variety of conventional and strategic arms negotiations and treaties is laying the groundwork for reduced military forces and expenditures. As these forces shrink, the U.S. Navy's Trident Fleet Ballistic Missile submarine fleet is likely to inherit an increasingly important strategic deterrent role. The SSD will continue supporting the Navy's requirements to assure the readiness and survivability of this fleet and will focus its skills and expertise on other high-priority national programs as needed.

REFERENCES

[1]Diamond, E., *The Rise and Fall of the Space Age*, Doubleday, Garden City, N.Y. (1964).
[2]Friedman, N., *U.S. Naval Weapons*, Conway Maritime Press, London (1983).
[3]Sapolsky, H. M., *The Polaris System Development*, Harvard University Press, Cambridge, Mass. (1972).
[4]*FBM Facts/Chronology, Polaris Poseidon Trident*, Strategic Systems Project Office, Department of Navy (1986).
[5]Baar, J., and Howard, W. E., *Polaris!*, Harcourt, Brace and Company, New York (1960).
[6]"Rocket Propellant of Aluminum Hailed," *New York Times* (19 Jul 1959).
[7]Levine, A. I., *The Future of the U.S. Space Programs*, Praeger Publishers, New York (1975).
[8]Gilreath, H. E., "The Beginning of Hypersonic Ramjet Research at APL," *Johns Hopkins APL Tech. Dig.* **11**(3&4), 319–335 (1990).
[9]*The First Forty Years*, The Johns Hopkins University Applied Physics Laboratory, Laurel, Md. (1983).
[10]*APL News*, "Laboratory's Transit Success Hailed Around World" (Apr 1960).
[11]*APL News*, "APL Had Important Role in Launching Polaris" (Aug 1960).
[12]*APL News*, "Navy Honors Dr. Kershner and the Laboratory for the Polaris Program" (Feb 1961).
[13]Berman, R. P., and Baker, J. C., *Soviet Strategic Forces: Requirements and Responses*, The Brooking Institution, Washington, D.C. (1982).
[14]Parry, A., *Russia's Rockets and Missiles*, Doubleday, Garden City, N.Y. (1960).
[15]*Jane's Fighting Ships*, Jane's Information Group, Surrey, England (1958–1991).
[16]*Jane's Strategic Weapons*, Jane's Information Group, Surrey, England (1990).
[17]*APL News*, "APL Credited with Concept of Moveable Nozzle" (Feb 1959).

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