Strategic Systems Fire Control

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The Naval Surface Warfare Center, Dahlgren Division (NSWCDD) has been an active participant in the Submarine Launched Ballistic Missile (SLBM) Program for nearly 40 years. The initial involvement resulted, in part, from a long history in exterior ballistics and a computing capability that was second to none in the Navy. Over the years, NSWCDD has been in the forefront of advances in trajectory modeling, geodetic systems and models, and computer science. NSWCDD experience in these fields played a key role in the development and targeting of the first SLBM—the POLARIS (A1)—and of every SLBM since. The weapon system requirements for greater range, better accuracy, and increased targeting and operational flexibility have been met, in part, because of NSWCDD advances in computational methods, computer languages and operating systems, and fire control system architecture. Development of the SLBM fire control system of the future will be motivated by different forces than have driven change in the past. Nonetheless, NSWCDD is continuing to use its knowledge and experience in mathematics and computing to anticipate SLBM weapon system needs and to propose innovative fire control and targeting solutions.

Introduction

On 15 November 1960, USS *George Washington* (SSBN 598) departed Charleston, SC, on the first nuclear deterrent patrol. It carried, in addition to 16 POLARIS A1 missiles, some 300,000 target cards prepared by the U.S. Naval Weapons Laboratory (now NSWCDD). Thirty-five years and some 3000 patrols later, fleet ballistic missile submarines (SSBNs) continue to deploy with fire control and targeting products developed by NSWCDD. The Division's expertise in mathematics and computing provided the basis for the initial support of the Special Projects Office (SPO) in 1956. It is still a primary reason that the Division has been able to develop fire control and targeting systems that have allowed full usage of the inherent capability of each of the successive generations of SLBMs (see Figure 1). This article will provide an overview of the technological advances in SLBM fire control and targeting from POLARIS to TRIDENT II and will conclude with a preview of planned and possible changes for the future.

POLARIS

In November 1955, the Secretary of the Navy established the SPO to investigate the unique problems associated with launching an intermediate-range (1500 NM) ballistic missile from a ship. The Army Ballistic Missile Agency was given the responsibility of developing the missile

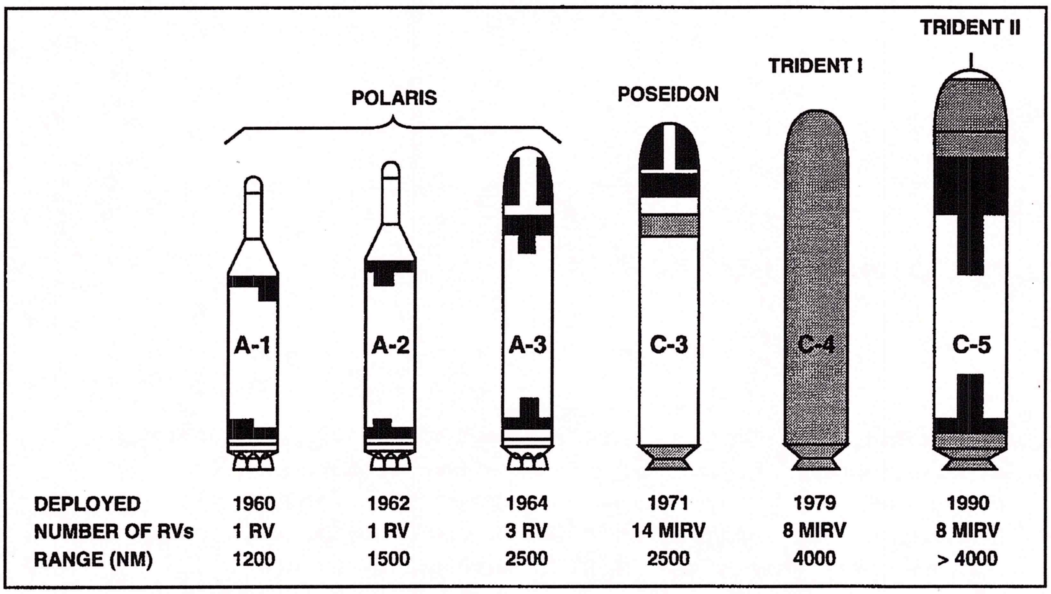

Figure 1. *SLBM evolution.*

and the land-based launching system. By the end of December, an operational requirement was issued, and specific research and technology needs were identified. Throughout much of 1956, the Army and the Navy studied the Army's JUPITER missile for ship and land-based use. NSWCDD's participation began during this period. By the end of the year, the JUPITER concept was discarded, and a Navy concept for a small, solid propellant missile was authorized by the Secretary of Defense. It was decided (by February 1959) that an interim 1200-NM capability (POLARIS A1) would be provided by late 1960 with full 1500-NM capability (A2) in mid-1962. An advanced 2500-NM capability (A3) was required by late 1964.

Dr. Russell Lyddane and Mr. Ralph Niemann visited SSP and presented Dahlgren's capabilities in exterior ballistics and computing. Dahlgren was the Navy's expert in classical exterior ballistics and had produced bombing and range tables since before World War II. Dahlgren's computer resources were also unmatched in the Navy. The Naval Ordnance Research Calculator (NORC), the Navy's foremost digital computer, had been installed in 1955, replacing the Aiken Relay Calculator (MARK II and MARK III). Dahlgren possessed unique expertise in trajectory modeling, having developed what is believed to be the first six-degree-of-freedom trajectory simulation (of a 12.75-in. rocket) in 1950.[1] At about the same time, Dahlgren was supporting the Naval Research Laboratory (NRL) development of the Vanguard satellite through efforts in orbit analysis.[2] This and associated research concerning modeling of the earth's gravity field were aspects of Dahlgren's unique mathematical and computational capabilities, which supported the early POLARIS studies. The earliest of these studies involved the evaluation of guidance presetting methods in support of Q-matrix guidance developed by the Massachusetts Institute of Technology (MIT) Instrumentation Laboratory.

Organizational Evolution–When NSWCDD first began supporting the POLARIS program, we were known as the Naval Proving Ground. By the time the system deployed, we were the Naval Weapons Laboratory. Later, we became the Naval Surface Weapons Center. Similarly, Strategic Systems Programs (SSP) began as Special Projects Office (SPO), became the Strategic Systems Project Office in 1968, the Strategic Systems Program Office in 1984 and, finally, SSP in 1987.

Q Guidance–Q guidance is a form of implicit (i.e., does not require knowledge of missile position) guidance developed by Laning and Battin at the Massachusetts Institute of Technology (MIT).[3] This scheme uses the elements of the Q matrix (which are the partial derivatives of the components of the correlated velocity with respect to the components of the position vector) to compute the required change in the velocity to be gained and, thus, to update an initial estimate of velocity to be gained. When the cross product of the velocity to be gained and its rate of change are nulled, thrust is terminated, leaving the missile on a ballistic trajectory to the target. This concept minimizes in-flight computation and does not require an in-flight gravity model. Both were significant attributes since sufficiently capable and reliable flight computers were beyond the state of technology.

These early studies of the POLARIS missile and its guidance led to Dahlgren being assigned the role that it has filled for every SLBM system since—providing the development of fire control and targeting products. It should be noted that one of SSP's key maxims was that naval laboratories were to be used in the development effort only if their technical competence was not available in private industry.[4] Inherent technical capability and the availability of computing resources were a prerequisite for being assigned a role in POLARIS; however, demonstrating (and continuing to demonstrate) technical competence to SSP was the key factor.

POLARIS Fire Control

In general terms, SLBM fire control:

- Initializes missile guidance with navigation and targeting data
- Aligns and erects the inertial guidance system (i.e., determines the direction of north and vertical)
- Checks the status of other shipboard systems
- Controls the launch sequence

The presetting data for POLARIS were basically the elements of the Q matrix—it was shown that once they are computed from launch and target coordinates, they can be treated as constants for typical POLARIS ranges—and an initial value of velocity to be gained. Computation of these data, which are used to direct the flight of a ballistic missile to the intended target, requires a suitable trajectory model, earth and atmospheric models, and appropriate target information. If this missile is to be fired from a moving platform, these computations will ideally be done immediately before launch using real-time navigation inputs.

In the late 1950s, when Dahlgren was addressing this problem, computer technology did not support this approach. Computers were too large for shipboard installation and too unreliable to be placed in the critical path for launching a weapon. An alternative was to provide direct input of precomputed initial conditions for a large number of possible launch-target point combinations.[5] This approach had two significant shortcomings: it required the submarine to carry a very large amount of data (in the form of punched cards), and computing these data would take an extremely long time on the NORC. Each trajectory calculation on the NORC took 1½ hours of computer time, and it was estimated that 40 years would be required to prepare all of the cards needed for the first patrol.

The solution developed by Dahlgren was a modification of the precomputed data approach. The launch area was divided into 20-NM squares and the target area into 30-NM squares. Presetting data were computed for each of the required pairs and provided to the submarine on punched cards. The data required to interpolate for points within the cells were also provided. Even with this reduction, however, the computational burden on the NORC was still excessive—a large number of trajectory simulations was required. Dahlgren mathematicians solved this problem by running only enough trajectories to develop numerical functions for each of the guidance presettings in terms of launch-point coordinates and target range and bearing. These functions were used to generate the data transferred to the submarine on target cards. Data were read from the appropriate card (see Figure 2) and entered into the Mark 80 Fire Control System (FCS) using knobs and dials on the input panel. The target card also contained the solution to a test problem, which was used to verify the manual knob settings. This process, as unwieldy as it was, proved to be successful. Dahlgren provided target cards for all operational patrols and for all guided flight tests.

Dahlgren developed or initiated two improvements to the system to address the logistics problems. The first of these was to provide the target cards on microfilm (three cards per frame). A film reader and keypunch were placed on the SSBN so that the crew could produce cards as needed. When the boats were deployed with the A3, an additional upgrade was required, and the Mark 148 POLARIS Target Card Computer System (PTCCS) was developed. The PTCCS was a stand-alone system (not part of fire control) that used Dahlgren-provided programs and data to produce POLARIS target cards. This system (which had 8000 words of memory and averaged 66,000 operations per second) was used until 1982 when the last of the original 10 POLARIS submarines was withdrawn from service.[6]

Mark 84 Fire Control

The Mark 80 FCS was installed on the first ten submarines; it was replaced by the Mark 84 on the 31 Lafayette-class SSBNs. This system, which used the first digital fire control software developed by Dahlgren, became operational in 1963 with the A2 missile. The heart of the system was the Digital Geoballistic Computer (DGBC). It consisted of two Digital Control Computers (DCCs)—a militarized version of a CDC 1604 commercial computer—with access to a common magnetic drum, printer, and punched tape reader. Each DCC had 16,000 words of core memory and averaged some 87,000 operations per second. Dahlgren program and data updates were delivered to the submarine on punched tape and loaded on the magnetic drum.

The FCS performed real-time fire control computations and controlled initialization of the guidance systems for 16 POLARIS missiles. In general terms, the complex POLARIS presetting functions, which were previously solved at Dahlgren to produce target cards, were now solved by the FCS. The results were based on real-time navigation inputs and were periodically updated. The Mark 84 is no longer in service in the U.S. SLBM force. The U.K. signed an agreement with the U.S. in 1963 to purchase the POLARIS A3 system. The Mark 84 FCS- and Dahlgren-produced software are still in service with the U.K. SLBM force.

POSEIDON (C3)

As early as 1962, SSP (and others) began considering a follow-on to A3. The first concepts addressed increased payload at the same range as A3. The larger missile being proposed

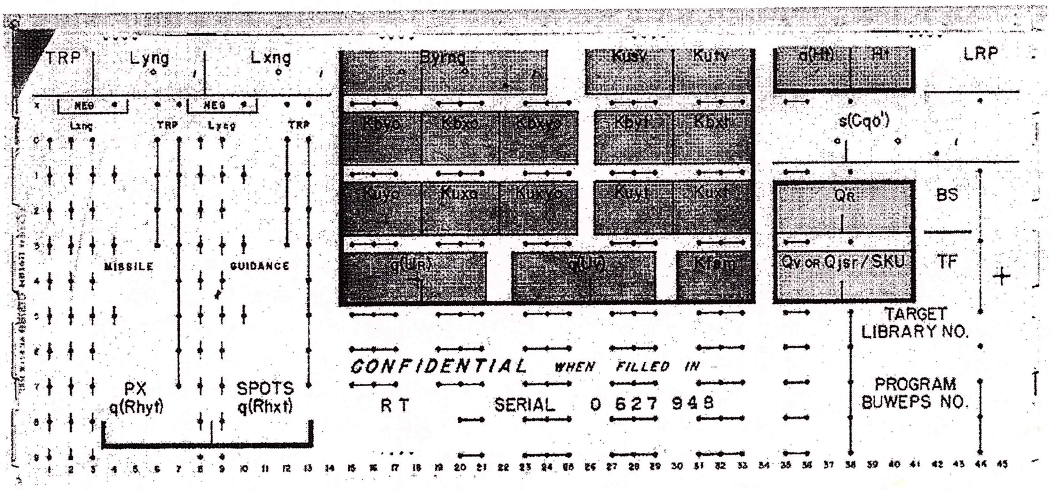

Figure 2. *POLARIS Mark 80 FCS target card.*

was called POLARIS A3A. There was some concern in DoD as to whether or not the A3A would satisfy long-term requirements.[7] During 1963 and early 1964, a variety of reentry systems were considered. In 1964, DoD decided that the next SLBM would be designed to be effective against urban-industrial targets and that it would carry the Mark 12 reentry body (RB) being developed by the Air Force. The resulting missile was larger than the A3A and was referred to as the POLARIS B3. Secretary of Defense Robert S. McNamara recommended development of the B3 to the President in December 1964. In January 1965, President Lyndon B. Johnson announced the development of the next generation SLBM—the POSEIDON C3. The name was apparently changed to emphasize that this was a new system. The POSEIDON C3 became operational in March 1971 when USS *James Madison* (SSBN 627) deployed on an operational patrol.

Studies performed during 1964 indicated that the B3 could carry up to six Mark 12s (compared to one RB on A1 and A2, and three on A3). Several RB deployment schemes were considered. The first choice was to deploy them in a pattern around the target point as was done in A3. The A3 ejection mechanism did not allow a large enough RB separation at the target, and other concepts were proposed. The top candidates were known as *Mailman* and *Blue Angels*. *Mailman* proposed to put a guidance and propulsion system on a post-boost vehicle (or bus) that would carry all of the RBs and release them one at a time to achieve the desired pattern at the target. *Blue Angels* required that each RB have its own guidance and propulsion system. One significant drawback with *Mailman* was that Q-matrix guidance could not be used, because explicit knowledge of missile position was required to properly deploy the individual RBs. *Blue Angels*, on the other hand, would retain Q-matrix guidance. *Mailman* was considered the more elegant solution and was chosen.

Modeling Earth's Gravity Field

Dahlgren became involved with these studies during 1964. Among the first issues were determining the proper guidance algorithm and identifying the associated guidance presettings to be computed in fire control. One implication of explicit guidance is that the in-flight guidance system must use a model of the earth's gravity in its calculations. Since the late 1950s, Dahlgren had been active in orbit determination and, in 1960, used Doppler observations of the Transit 1B satellite to verify the "pear shape" of the earth's gravity field.[8] In the early 1960s, Dahlgren pioneered the development of what was called a "General Geodetic Solution," which provided the simultaneous determination of gravity coefficients, ground tracking station coordinates, and an assortment of sensor and measurement system biases. These preliminary solutions led to the development of the standard Department of Defense (DoD) gravity model—the World Geodetic System 1966 (WGS-66). (Dahlgren has continued to develop this system. Later versions, WGS-72 and WGS-84, have also been DoD standards and were used in later SLBM systems.)

These developments and the POLARIS fire control experience put NSWCDD in a unique position to solve the guidance gravity model problem. The solution proposed by NSWCDD utilized the capabilities of both fire control and in-flight guidance. Guidance used Keplerian equations with an inverse square (or round earth) gravity model for in-flight calculation of position and steering commands. Fire control compensated for the inherent error (due to both the simplified gravity model and guidance's lack of an earth atmosphere model) by calculating offsets to be added to the target vector used in the guidance computations. These offsets (or "Kentucky Windage") are a function of launch point, target point, and the specific trajectory to be flown; and require modeling the guidance computations in a trajectory simulation with higher fidelity gravity and atmosphere models. Ideally, this computation would be done in fire control using real-time navigation inputs. However, this was not possible, and an approximate method was developed for fire control use.

Mark 88 Fire Control

The Mark 88 Mod 0 (and, later, Mod 1) FCS was developed for C3 and replaced the Mark 84 on the 31 *Lafayette*-class SSBNs (see Figure 3). This system closely resembled the Mark 84 but

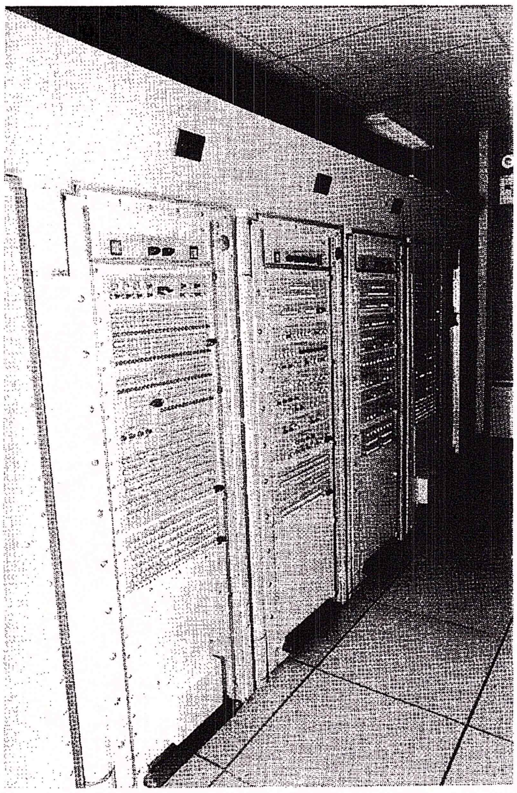

Figure 3. *POSEIDON Mark 88 Fire Control System.*

had several significant additions. The shared magnetic drum was replaced by two magnetic disk file systems, which provided more than an order of magnitude more mass storage, and a keyboard was added to improve the operator interface. The basic computing power, however, was much like that of the Mark 84. Fire control programs and data were sent from Dahlgren to the submarine on magnetic disk packs. Targeting data could be changed onboard the SSBN by entering data (by keyboard or punched tape) to a reserved area on the disk pack.

The fire control presetting calculations were estimated to be an order of magnitude more complex than those for POLARIS, and 20 times the number of guidance presettings were computed. This was the result of the more complicated guidance scheme used in C3 and the fact that there were now multiple independently targetable reentry vehicles (MIRVs) to be considered. Fire control computed the booster presettings and the offsets for each RB target, and checked the achievability (i.e., sufficiency of bus energy to release all RBs with required velocity). In previous systems, all flights were on minimum energy trajectories. POSEIDON fire control provided the capability to select a time-of-flight option. As before, fire control allowed real-time control of the system by providing computer control of the guidance erection and alignment process, by providing the interface between navigation and the missile, and by checking the status of the shipboard systems required to launch the missile. Dahlgren's growing expertise in computer science was the key to finding a way to solve the more complex POSEIDON fire control problem in what was basically a POLARIS computer. This solution included developing efficient algorithms and applying innovative methods in computer science. Dahlgren developed a unique computer operating system (the POSEIDON SUPERVISOR) that controlled relocatable programs (i.e., managed memory) in order to simultaneously prepare all 16 missiles to be launched. In the end, there was actually an increase in overall FCS performance.

At the same time, the Joint Strategic Targeting Planning Staff (JSTPS) was wrestling with the problem of targeting a MIRV system. Previously, targeting was primarily a matter of assigning a target to the one warhead on the missile and making sure that the target was within the range of the missile. The MIRV problem was much more complex. Each warhead on the missile had to be assigned a target, and a "footprint" had to be developed. Maximizing the separation of the

In a MIRV system, each warhead is assigned to an "aimpoint" (or target), and all aimpoints assigned to warheads on the same missile are collected in "footprints." Footprints are an ordered set of aimpoints and are constrained in geographic extent by the capabilities of the equipment section and the trajectory shape. Multiple footprints are collected in "target packages." All footprints in a target package will be struck by missiles from the same SSBN.

JSTPS –The JSTPS was established by President Eisenhower and Secretary of Defense Thomas S. Gates in August 1960. It was located at Offutt Air Force Base (AFB) in Omaha, Nebraska. The Director was the Commander in Chief of the Strategic Air Command, and the Vice-Director was always a Navy flag officer. This function is now performed by the U.S. Strategic Command.

individual ground targets required determining the optimum sequence in which they should be struck (and thus, how they should be assigned to RBs on the bus, because RBs are released in a specified order to preserve bus stability). This was not a job that could be accomplished with the simple tools available to JSTPS. Suitable computer models were developed at NSWCDD and supplied to JSTPS. Dahlgren has provided such models and guidance for all SLBM systems ever since.

Quality Assurance and Configuration Management

Dahlgren's other major contribution to POSEIDON was the development of a quality assurance and configuration management system for fire control and targeting products. While this was done on earlier systems, the stringent testing and configuration control that characterizes SLBM has its origins in POSEIDON. The process has evolved with each of the successive systems and, at SSP's direction, has been applied by other SLBM contractors. It was a model for similar efforts (such as TOMAHAWK) at Dahlgren.

TRIDENT I (C4)

While POSEIDON development was underway, consideration of the next generation SLBM system began. In late 1966, a study called "STRAT-X" examined alternatives to counter a Soviet antiballistic missile (ABM) threat. The Navy concept that emerged from this study was known as the undersea long-range missile system (ULMS). It was a larger missile than POSEIDON or POLARIS and would require the development of a new submarine. By 1971, two specific alternatives had emerged: ULMS and a new submarine, or an extended-range POSEIDON (called EXPO) that could be carried on Lafayette-class SSBNs. It appeared (based largely on submarine construction schedules) that ULMS could not be deployed until the early 1980s (possibly as late as 1983). EXPO, on the other hand, could be fielded in late 1977. Dahlgren supported SSP and the Chief of Naval Operations' (CNO) staff in defining the basic requirements for this new SLBM system.

The Secretary of Defense announced his ULMS decision on 14 September 1971. ULMS I would be a 4000-NM missile that was compatible with the POSEIDON submarines. ULMS II would be a longer range missile to be deployed in a new submarine. ULMS I would be deployed in 1977; no specific deployment date was set for ULMS II. ULMS was renamed TRIDENT in May 1972. The TRIDENT I C4 became operational on USS *Francis Scott Key* (SSBN 657) in October 1979 and on USS *Ohio* (SSBN 726), the first large submarine, in October 1982.

SSP resisted (as they had on previous systems) setting accuracy objectives for C4. Instead, the goal was to increase missile range to 4000 NM, while maintaining C3 accuracy. The longer range was needed to increase sea room for the submarine in order to counter the Soviet antisubmarine warfare (ASW) threat. Accomplishing this required that the system be more accurate, as target miss tends to increase with range. One of the key changes to the system was the addition of a stellar sensor to the guidance system; another was higher fidelity fire control compensation for gravity effects. Dahlgren had a hand in the development and implementation of both.

TRIDENT I takes a star sighting before release of the reentry bodies. A preselected star is located, and two error coordinates are measured. These coordinates, which represent angular rotations about two of the three axes of the guidance coordinate frame, are combined with a precomputed weighting (W) matrix (based on statistical estimates of weapon system errors) to estimate guidance position, velocity, and orientation errors. These estimates are then used to update the guidance computer. Some of the early work on stellar guidance began during the development of C3. Dahlgren contributed to the analysis of its accuracy potential and, in particular, of the operational implementation issues.

Dahlgren's contribution to stellar guidance took two specific forms in addition to the more general concept analysis. These were the development of the fire control computations required to select the optimum star for accuracy and compute the W matrix for a given launch point and target point combination, and the development of the operational star catalog. Both star selection and W-matrix computation are based on knowledge of star location, weapon system error sources and modeling, and trajectory conditions (including launch and target coordinates). Since star position is a function of time of day, launch point, and trajectory conditions—all of which change as the submarine moves—these computations must be performed in fire control near the time of launch (or performed in such a way that they are relatively insensitive to changes in time or position). Further, they had to be defined so that they maintained the readiness time and launch rate of POSEIDON. These computations were all developed by Dahlgren and met all timing and accuracy requirements.

The operational star catalog had to meet certain requirements—included stars had to:

- Exceed a minimum brightness
- Have a relatively constant brightness
- Have a minimum separation from other stars
- Have a predictable position

It turned out that there was no star catalog that met all of these requirements. Dahlgren obtained several of the standard catalogs and analyzed and compared them. They did not always contain the same stars or, if they did, there was not always agreement on position data, brightness, or the coefficients used to update star position from the reference epoch to the current time. Dahlgren resolved many of the discrepancies and produced the "Dahlgren General Catalog." This, in turn, was used to select the subset of stars that constitute the C4 operational catalog.

TRIDENT I fire control is also distinguished by the fact that it uses an onboard trajectory model to compute guidance presettings. Previous fire control computations compensated for the oblate gravity terms in the model of the earth's gravity. Tesseral gravity effects were compensated for as part of the target offset functions derived at Dahlgren. Maintaining C3 accuracy at the longer C4 ranges required more accurate compensation at the tesseral gravity level. Further, this compensation and other presetting computations led to the need for a trajectory model in fire control in place of the evaluation of functions developed at Dahlgren. A basic requirement, noted above, was that readiness time and firing rate could not be affected. The development of a fast (and sufficiently accurate) trajectory model that executed on the TRIDENT I fire control computer was a major accomplishment.

Mark 98 Fire Control

The Mark 88 Mod 2 FCS was developed for use with C4 on the backfitted POSEIDON submarines. The Mark 98 Mod 0 FCS was used with C4 on the larger USS *Ohio* (SSBN 726) class TRIDENT submarines. Dahlgren was intimately involved in determining the design characteristics and architecture for both of these FCSs. The design used the Mark 88 technology as a base and added some significant improvements. These included replacing the DCC with a more capable computer known as the TRIDENT DCC (TDCC) and adding

Earth's Gravity Field–The earth's gravity field can be represented as a series of spherical harmonics. The first term is the inverse square (or, round earth model). Adding the second (the "J2") term causes the earth to be represented as an oblate spheroid. At NSWCDD (and in SLBM), the next set of terms (up to degree and order nine) are often referred to as the "tesseral" gravity terms. The remaining very localized effect is generically called "high-frequency" gravity.

magnetic tape cartridges (MTCs) to supplement the magnetic disk packs. The disk packs were no longer adequate to store all of the required data, and the capability was added to read targeting and geophysical data from the MTCs. In addition, fire control test data and some guidance data are provided on MTCs.

Perhaps more significant overall were the fire control software changes implemented for TRIDENT I. Based on the expected complexity of the C4 fire control software, NSWCDD recommended to SSP that some fundamental changes were required. These included a new real-time operating system and the use, for the first time, of a higher level programming language. The new operating system was developed completely by NSWCDD. It allowed partitioning of the software and met all of the real-time support requirements. (Much of this was in support of the erection and alignment of the guidance system. This was digitally (software) controlled in C4 rather than analog, as in previous systems.) NSWCDD also developed a nonintrusive measurement and debug system that extracted data from the FCS in real time. This system, the Verification and Evaluation System for TRIDENT (VEST), was the model for the same capability in the UYK-43, a standard shipboard computer in the surface navy. Dahlgren developed the TRIDENT Higher Level Language (THLL) used in C4 fire control as well as the associated compilers, linkers, loaders, and other support software. Fire control software for previous systems was written in machine language. It was estimated that it took two to three years to become proficient at this. Thus, another benefit was the relative quickness with which new employees could contribute to the development. This was aided further by the addition of structured software techniques to the software development process at Dahlgren. NSWCDD was in the forefront of developments in structured programming and quality assurance during this period.

TRIDENT II (D5)

The CNO, ADM Elmo R. Zumwalt (in 1972) and the Secretary of Defense, James Schlesinger (in 1973), asked for information on possible accuracy improvements to the SLBM system. Schlesinger, in particular, felt that the nation's security needs could be better satisfied with a more accurate system. SSP was reluctant to commit to a more stringent accuracy requirement, because they lacked the ability to measure error contributions and the understanding required to extrapolate results to other than the test conditions. The Improved Accuracy Program (IAP) was the result of discussions between Schlesinger and the Director of SSP, RADM Levering Smith. Spanning from 1974 to 1982, this program had several objectives:

- Gaining an understanding of SLBM error sources
- Assessing the accuracy potential of improved components and concepts
- Starting advanced development of promising components and concepts

A major thrust was developing new instrumentation methods so that the needed error source data could be gathered.

Dahlgren participated fully in the IAP program. New concepts such as the "Inverted Global Positioning System (GPS)" (a system whereby the then-incomplete GPS constellation could be augmented by ground stations), GPS-aided guidance, and terminal sensors on reentry bodies, represent some of the concepts investigated by Dahlgren to assess accuracy potential or to identify operational issues. Improved fire control methods, such as high-frequency gravity modeling and compensation, were developed. Similarly, NSWCDD contributed to the investigation of improved stellar guidance concepts. Flight tests were supported, either by mission planning and postflight analysis or, in the case of the SATRACK system, by producing precise GPS ephemerides for postflight estimation of errors. One of the major lessons of IAP (and one that Dahlgren contributed to learning) was that a total-system approach was required to develop a very accurate system. It was no longer sufficient to optimize accuracy at a subsystem level. A systems-engineering approach based on the specification of system and subsystem error budgets verified by precise measurements and computer simulation (first developed for TRIDENT I) was expanded and used for TRIDENT II.

In 1977, Congress authorized funding for initial TRIDENT II (D5) studies. There were a number of issues to be resolved including missile configuration (i.e., payload weight and type) and accuracy requirements. SSP's initial desire was to carry the C4 reentry body (the Mark 4) in greater numbers or to a greater range. There were external pressures to develop a more accurate missile. Finally, in October 1981, an advanced development program (for a late 1989 Initial Operational Capability (IOC)) was authorized. The system was to carry a new higher yield Mark 5 reentry body (while maintaining the capability to carry the Mark 4) and to be highly accurate. IOC for the TRIDENT II D5 was achieved in March 1990.

A number of system changes were needed to achieve the required accuracy. These included modifications to the guidance system (including a new inertial measurement unit (IMU) and a new stellar sensor), a new navigation system (Electrostatically Supported Gyro Navigation (ESGN) instead of ship's inertial navigation system (SINS)) as well as other modifications to the navigation system (such as a Navigation Sonar System to measure velocity), and a new equipment section (bus) and RB release mechanism. Fire control computations were also changed. A more accurate compensation of gravity (including high-frequency gravity) was required. Compensation of reentry wind and density effects and the fire control computations, in general, were made more accurate. Changes were also required to support the new stellar sensor. These included the development by Dahlgren of a new weighting matrix and update scheme and a new operational star catalog. A key, as highlighted previously, was that the fire control software had to be designed to pull the entire weapon system together to achieve overall goals.

Dahlgren innovation in gravity modeling is particularly noteworthy. The earth's gravity field is often represented as a spherical harmonic series, which is constructed using measured data. Much of the data used for this purpose can be obtained from satellite altimetry; the high-frequency part (being very localized) usually requires surface surveys. Computation of gravity at altitude, such as in a trajectory model, can be accomplished in several ways. In guidance, and other simple trajectory models, the simple inverse square equation is often used. This can be extended to include the oblateness effects. Higher fidelity models, such as those needed for D5 fire control, make use of the higher degree and order terms in the spherical harmonic series and the measured data.

Gravity at altitude is computed from a Stoke's integral formulation using a process known as ***upward continuation***. In theory, this process requires the integration of gravity effects over the entire earth to compute gravity at a single point in space. As a practical matter, the value of gravity at a point in space is more dependent on surface gravity at points in close proximity to a position directly under it. Dahlgren developed a kernel for the Stoke's integral that uses only the required points and a unique circular template of gravity data for use in the integration. The template, which is constructed in fire control, is centered at the point on the earth under the point in space and combines gravity data from different fidelity databases in an optimum fashion. This unique, and now widely recognized, result was a key determinant in achieving the required D5 accuracy.

Mark 98 Mod 1 Fire Control

The Mark 98 Mod 1 FCS was developed for TRIDENT II. A number of changes were made to ensure that readiness time and firing rate were maintained; the architecture is illustrated in Figure 4. Some significant changes include increasing fire control memory, replacing the disk packs with a new fixed mass memory device, adding high-density magnetic tapes to transport programs and data to the submarine, and adding digital interfaces (with microprocessors) between fire control and guidance (GISS) and fire control and navigation (NISS). Dahlgren participated in identifying system requirements and in developing the architecture.

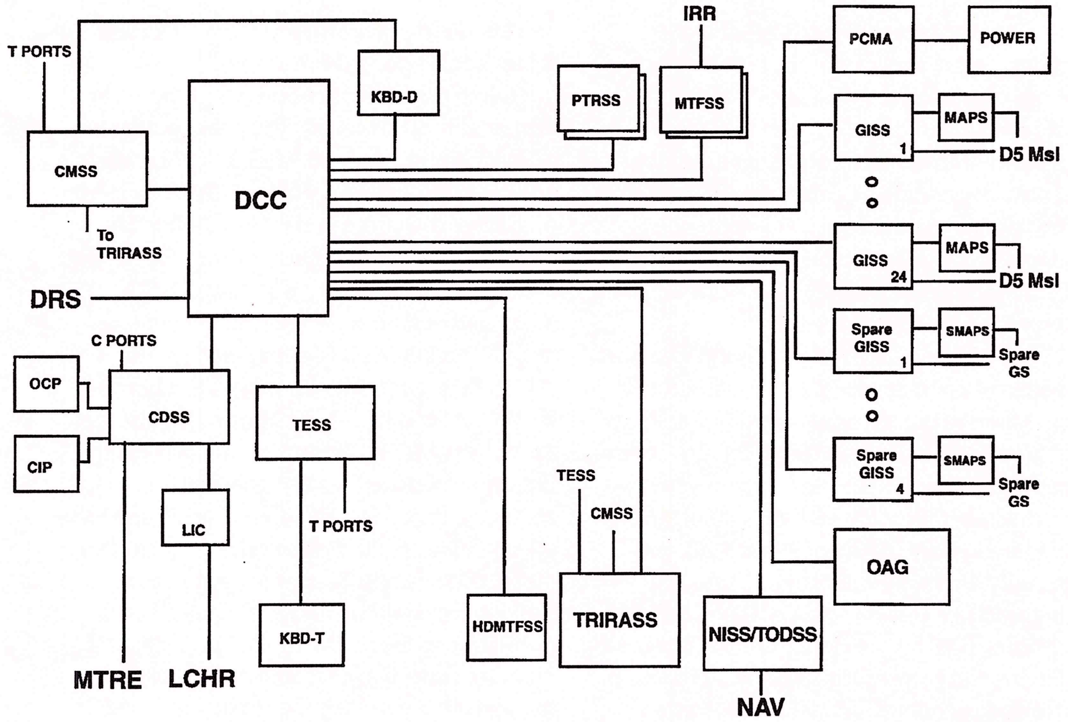

Figure 4. *Mark 98 Mod 1 architecture.*

The Future

The SLBM program has evolved in response to changes in the threat and in national policy. In 1959, the need was for a survivable system that supported the national policy of mutually assured destruction by providing a guaranteed retaliatory capability. Precise accuracy was not needed, nor was it achievable with the technology of the day. Initial upgrades to POLARIS were motivated by the need to increase range in order to provide greater submarine operating area and, hence, survivability. Later on, changes were made to accept new reentry bodies (and more than one per missile). Coincident with this was a need to improve and maintain accuracy at ever longer ranges.

The SLBM system has also changed in response to other needs. The U.S. nuclear policy, for example, has changed—from massive retaliation in the 1950s to flexible response in the 1970s and beyond—and the later SLBM system capabilities reflect this. Fire control changes reflect the increased need for targeting flexibility as well as the changes to the missile and guidance systems highlighted previously. Arms control agreements (from SALT to START II) limit the number and types of strategic systems available for nuclear deterrence. The reductions are inexorably moving the SLBM to a dominant position in the triad of nuclear deterrent forces. With this dominance comes the need for increased capabilities—such as D5's hard-target kill capability—and the need for flexible and responsive targeting.

What will motivate the development of future SLBM systems? Some would argue, based on the current world situation, that the need for nuclear deterrence is diminishing and that no system beyond D5 is needed. The recent Nuclear Posture Review established a continuing need for a D5 force, albeit with fewer Fleet Ballistic Missile Submarines (SSBNs), with the resultant need to "backfit" four of the original TRIDENT submarines so that they can operate with D5 missiles. Thus, increasing the operating life of the current system becomes critical. Studies (such as the "Future Deterrence Study" sponsored by the Strategy and Policy Division of the Office of the Chief of Naval Operations)[9] have considered the implications of the changing world situation and a range of threats possible in the future. Nearly all of them suggest a move away from the bipolar world that has characterized the Cold-War era to a world with a number of smaller nuclear-capable countries. They also tend to suggest that providing strategic deterrence in the future will require more than nuclear weapons. Conventionally armed submarine launched ballistic missiles (CSLBM) have been proposed as a means to meet these needs.

It could be argued that, in this environment, fire control upgrades are more important than ever. Inherent in increased targeting flexibility, for example, is a need for improved fire control capabilities. Implicit in life extension are increased operating life and supportability for shipboard systems. Any new warhead, and especially a conventional one, will require changes to fire control. NSWCDD is actively supporting SSP by providing solutions to these problems and by preparing special revisions of software to support flight tests of the new capabilities. Targeting upgrades are being addressed by the SLBM Retargeting System (SRS). This has resulted in both shore-based processing improvements at NSWCDD and changes in shipboard fire control.

Some shipboard systems pose long-term supportability concerns. The changes that will be made to the Mark 98 Mod 1 FCS architecture by 1996 (Figure 5) address these concerns. A comparison with Figure 4 highlights the major changes: replacement of the mass storage system and connectivity with the SSBN's integrated radio room (IRR) using magnetic tapes. The D5 Mass Memory Subsystem (MMSS) is the result of a joint effort between NSWCDD and Lockheed Martin Defense Systems (LMDS). It is an example of using industry standards and "off-the-shelf" components (the disk drive and optical drive units and the processor in the mass memory controller) in the SLBM system. Dahlgren established the subsystem requirements, participated in the evaluation of the hardware design (including processor selection), recommended the commercial computer language to be used, and developed an operating system kernel to interact with the TDCC as part of a distributed real-time system.

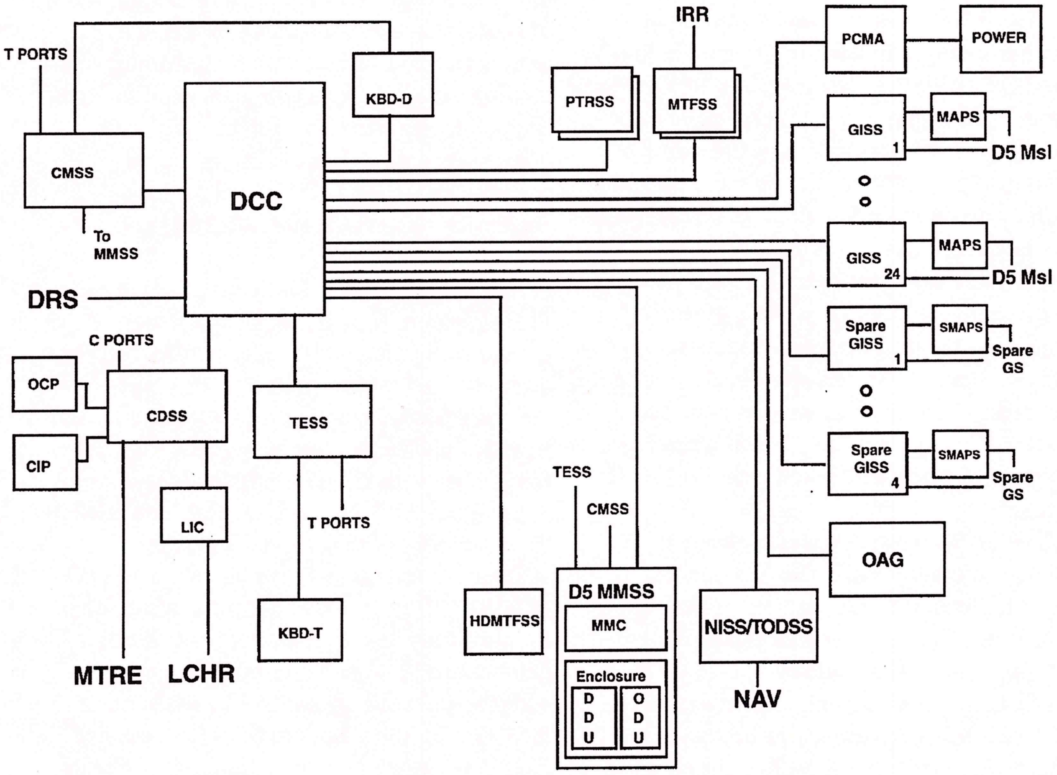

Figure 5. *Mark 98 Mod 1 architecture (1996).*

Longer term issues include upgrading the current FCS and addressing near- and far-term supportability concerns. The need for additional capabilities to address future requirements (targeting, for example) also drives redesign to meet future fire control needs and architectures. An example of a future architecture is given in Figure 6. This shows a fundamental change in architecture from the traditional computer-centered FCS to one that is fully distributed and which links all of the shipboard systems that make up the strategic weapons system. This new architecture reflects the changing nature of the SLBM fire control mission. Less obvious from this high-level view is that industry standard, off-the-shelf components (hardware, language, and operating system) will be used throughout the SLBM system. This architecture is flexible enough to support new requirements and reduce supportability costs, and is capable of being easily upgraded.

For nearly 40 years, NSWCDD has used its knowledge and experience in mathematics and computing to anticipate SLBM weapon system needs and to propose innovative fire control and targeting solutions. This effort is continuing and will help to ensure that the SLBM system can meet the changing requirements of its deterrent mission.

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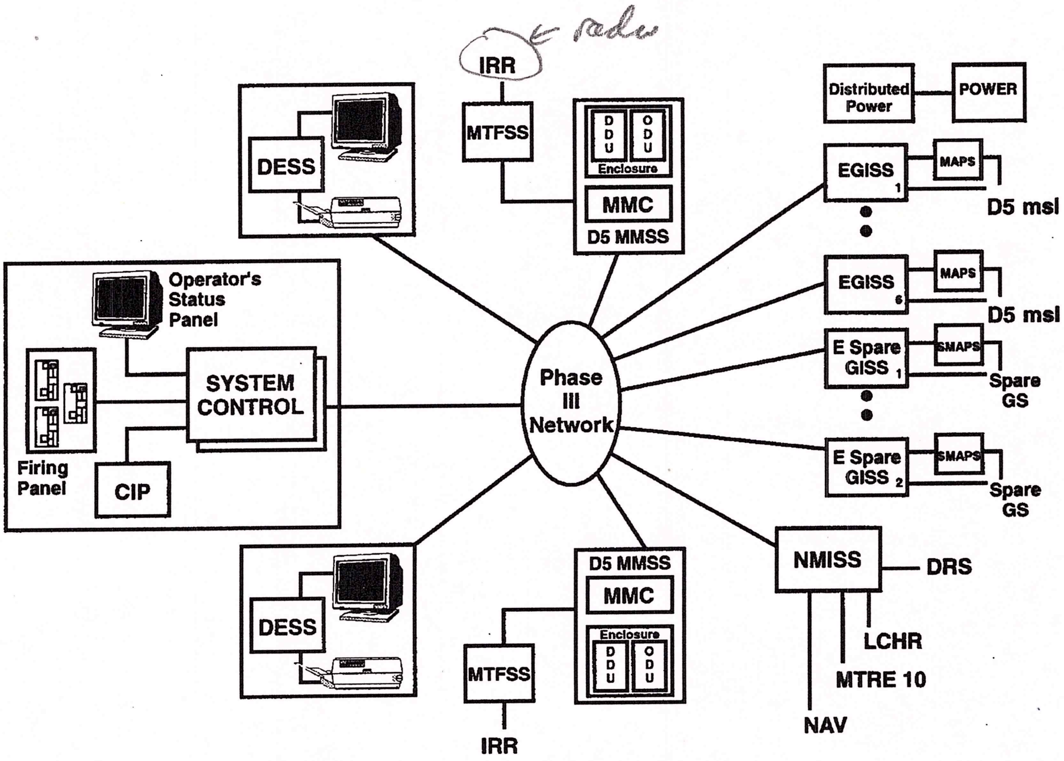
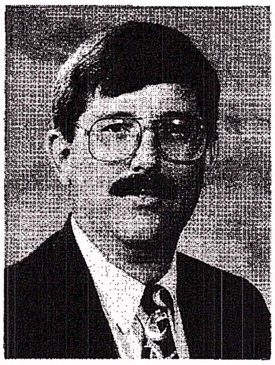


Figure 6. *Future fire control architecture.*

The Author



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