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STANDARD MISSILE: GUIDANCE SYSTEM DEVELOPMENT

To achieve a missile capability that is commensurate with the long-range, high data-rate, target-detection characteristics of the AN/SPY-1A radar, an evolutionary upgrade of the existing STANDARD Missile-1 was authorized. Designated STANDARD Missile-2, it adds a command mid-course flight phase, thereby providing the AEGIS Combat System with increased intercept range and higher firepower. STANDARD Missile-2 with inertial midcourse guidance also provides upgraded TERRIER and TARTAR Combat Systems with a corresponding increase in capability. Terminal guidance accuracy has also been improved by incorporating a new homing receiver common to all STANDARD Missile-2 variants.

INTRODUCTION

The development of STANDARD Missile-2 (SM-2) began in the early 1970's, with General Dynamics/Pomona as the Design Agent and APL as Technical Advisor. At the time, STANDARD Missile-1 (SM-1) was in production as the primary weapon for Fleet air defense by TERRIER and TARTAR ships. The principal modification to SM-1 envisioned at the outset was to add a midcourse guidance system consisting of communication links, a digital guidance computer, and an inertial reference unit. These additions were incorporated as shown in Fig. 1. For terminal guidance, the original plan had been to use the existing SM-1 scanning receiver. However, shortly after becoming the Naval Sea Systems Command AEGIS Project Manager in 1972, Rear Admiral W. E. Meyer made the decision to include a new monopulse terminal homing receiver. Thus, the final SM-2 configuration consisted of a largely new guidance section, a repackaged autopilot to accommodate the inertial reference unit, and the existing SM-1 ordnance, propulsion, and steering control systems.

To accelerate the development of the new homing receiver, General Dynamics/Pomona and APL engineers embarked on an intensive cooperative effort. The design evolved over a two-year period, during which frequent meetings were held to review every aspect of the signal processing and logic. During that time, the communication links had progressed to the point where hardware interface tests were being conducted to demonstrate ship system compatibility. Prior to the beginning of flight testing at White Sands Missile Range in 1975, a guidance section design model was supplied to APL for an assessment of its performance. Hundreds of hours of tests were conducted in the Guidance System Evaluation Laboratory. As that evaluation proceeded, SM-2 began to acquire a reputation as a highly accurate missile. The results obtained in the APL tests were confirmed in subsequent flight tests of SM-2 and an upgraded SM-1 that also uses the new homing receiver. To date, both missiles have achieved a sizable percentage of direct hits in intercepting target drones.

The development and deployment of SM-2 cannot realistically be a stopping point in providing the future Navy with an effective antiair warfare capability. Because the threat has continued to increase, the initial SM-2, now designated Block I, is being improved. Currently, Block II is in engineering development, with APL technical support being provided in many areas, including guidance.

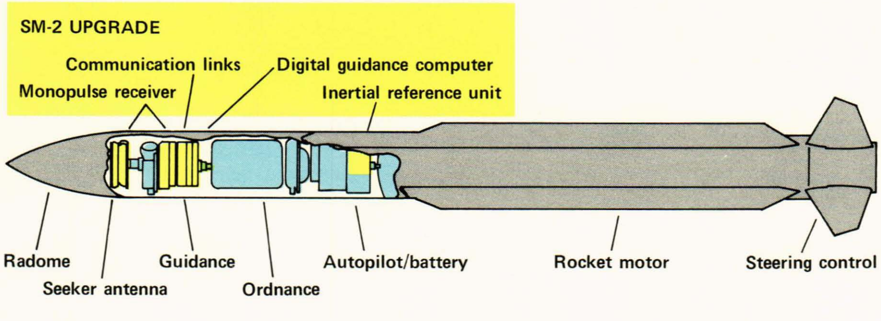


Figure 1 — STANDARD Missile-1 (SM-1) showing STANDARD Missile-2 (SM-2) additions. Evolutionary improvements to STANDARD Missile have been facilitated by the use of modular packaging. The SM-2 upgrade consisted of a new guidance section and additions to the autopilot/battery section, while other sections remained essentially unchanged.

MISSILE GUIDANCE TECHNIQUES

Semiactive Guidance

A feature common to both SM-1 and SM-2 is an ability to "home," i.e., to guide either some or all of the flight by means of target-reflected energy. The source of this energy is a high power, continuous wave, shipboard radar illuminator. A portion of the illuminator signal is received directly by the missile for use as a Doppler frequency reference. To accomplish this, the illuminator antenna combines a narrow beam directed toward the target with a broad reference beam that encompasses the missile throughout flight (Fig. 2). This type of guidance is called "semiactive" because the transmitter and receiver, although linked, are not colocated.

A semiactive missile must also be able to home passively on electronic countermeasures signals radiated by the target. Such signals may be used to screen the target-reflected signal or otherwise deceive the semiactive receiver. Home-on-jam processing is automatically selected when the target skin return cannot be identified and when incoherent energy is present whose frequency and angle of arrival are approximately correct.

Home-All-the-Way Guidance

A home-all-the-way guidance policy is one in which the missile derives its own steering commands throughout flight based on the processing of signals received from the target. Such a policy requires that the target be acquired either prior to or shortly after launch. Figure 3 illustrates the various phases in the firing of an SM-1, which uses home-all-the-way guidance. On the launcher, the missile is provided with a post-launch prediction of where it should look for the target in angle and Doppler frequency. Following an unguided boost phase, the missile seeker acquires either target-reflected energy from shipboard illumination or jamming energy emanating from the target. The seeker consists of a gimballed antenna and a radar receiver that measures the angle of arrival of the received signal (Fig. 2). The seeker tracks the target and provides information to the missile guidance computer concerning the line-of-sight angle and the closing velocity as determined from the Doppler frequency. Using a proportional navigation steering law, discussed below, the guidance computer generates steering commands that ideally keep the missile on a collision course with the target.

Semiactive, home-all-the-way guidance is used in many missile systems throughout the world. Its primary advantage is that it provides moderately good area defense coverage, i.e., intercept range, by virtue of high power ship-based or ground-based illumination combined with up-and-over flight trajectories. (Such trajectories are achieved by launching the missile at a relatively steep angle and allowing it to climb above the target early in flight so as to better maintain available kinematic energy.) One of the major limitations of home-all-the-way guidance is its relatively low firepower, since one of only a few illuminators must be committed to a single target for the entire missile flight. A second limitation is illustrated in Fig. 4, which shows the many signals that may be present at the missile's receiving antenna. Clearly, a missile receiver that must pick out the target signal immediately after launch has a much more difficult task than it would if acquisition could be delayed until later in flight.

Midcourse Plus Terminal Guidance

Midcourse guidance implies an intermediate flight phase in which an external source supplies sufficient information to allow the missile to guide or steer toward the target without having to home. Two types

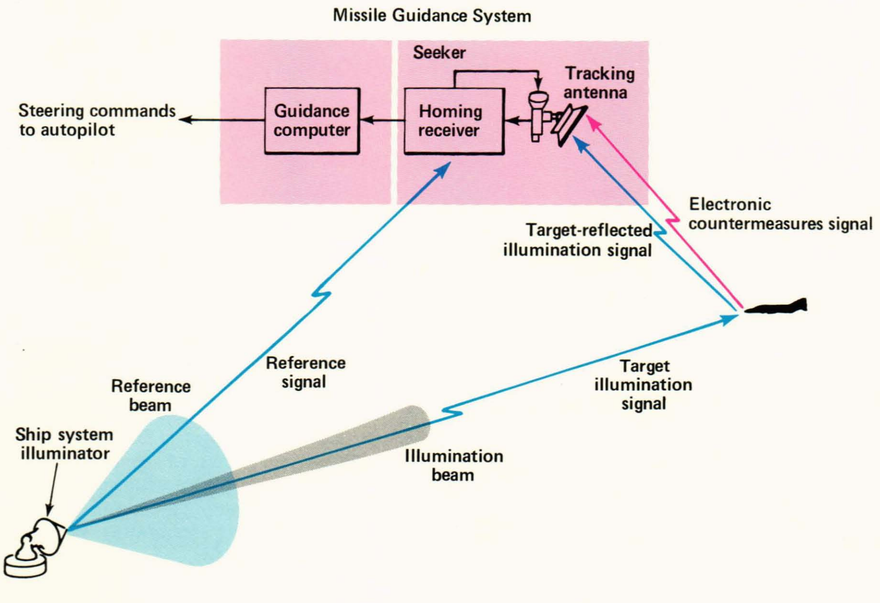


Figure 2 — Semiactive guidance concept. Both SM-1 and SM-2 employ continuous wave, semiactive guidance. The target is illuminated by highly pure, sinusoidal RF energy that allows objects to be distinguished on the basis of their velocity by the Doppler shift of the reflected energy. Homing is semiactive in the sense that the transmitter, in this case a high power shipborne radar, and the missile receiver are linked but not colocated. A passive homing capability is also provided to cope with possible jamming by the target. The combination of the onboard homing receiver and the steerable front antenna is known as a "seeker." In addition to target tracking, the seeker supplies information to the guidance computer for computing missile steering commands.

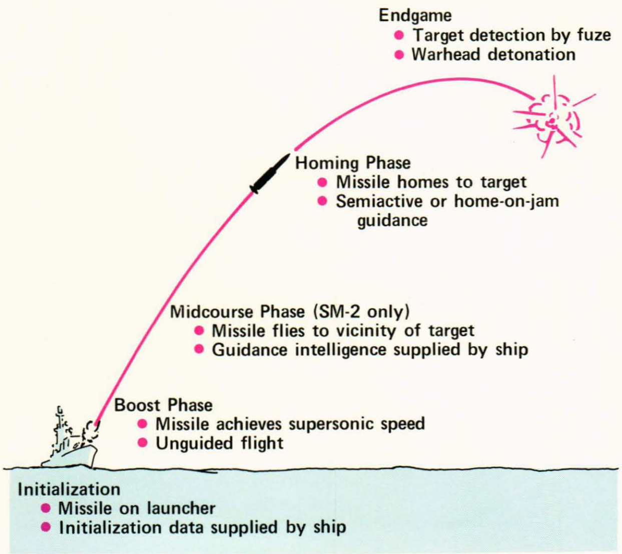


Figure 3 — STANDARD Missile operational sequence. On the launcher, the SM-1 is supplied with target acquisition data and begins homing shortly after the unguided boost phase of flight. The SM-2, however, undergoes a midcourse phase under ship control; at a predetermined point much later in flight, target acquisition occurs and homing begins. In the endgame phase, the target is detected by a missile-borne proximity fuze and the warhead is detonated close to the target.

of midcourse guidance are commonly used — command and inertial. In a command system, missile steering signals are directly supplied in an agreed-upon coordinate frame. In an inertial system, the missile guides toward a point or a succession of points in inertial space based on externally supplied information.

The use of midcourse guidance followed by a relatively short period of terminal homing offers a significant improvement in firepower and missile intercept coverage if the ship system can provide the necessary support. Firepower is clearly increased over home-all-the-way guidance because semiactive homing is restricted to the terminal portion of flight. Thus, the shipboard illuminators can be used more efficiently to engage a larger number of targets. If the missile has the kinematic capability and if the midcourse trajectory control is sufficiently accurate, then a small target can be engaged at a longer range than would be possible if seeker acquisition were required early in flight, as in the home-all-the-way case.

The shorter missile-to-target propagation distance at the start of the terminal homing phase also tends to enhance the target return relative to some of the sources of interference shown in Fig. 4. In particular, the missile has a much better chance of "seeing" the target in the presence of standoff jamming following a period of midcourse guidance than it would immediately after launch.

STANDARD MISSILE-2 MIDCOURSE GUIDANCE

Midcourse guidance has been implemented in SM-2 by adding to SM-1 an inertial reference unit together with missile-ship communication links. The inertial reference unit consists of an instrument package coupled with a special-purpose computer. The instruments include three accelerometers, two rate-integrating gyros for measuring angular motion perpendicular to the missile body, and a space-stable, single-axis platform for monitoring missile roll. The computer solves the equations of motion to keep track of missile position, velocity, and attitude in the inertial coordinate frame established prior to launch.

AEGIS Command Midcourse Guidance

In the AEGIS Combat System, SM-2 is command-guided during midcourse flight under direct control of the ship (Fig. 5a). The AN/SPY-1A radar performs missile and target tracking and also serves as the shipboard data link transceiver. Steering commands are computed by the ship weapon-control computer and transmitted on the uplink to the missile, which acknowledges receipt via the downlink. The midcourse guidance law is a form of proportional navigation with appropriate trajectory-shaping modifications. The inertial reference unit is used primarily as an atti-

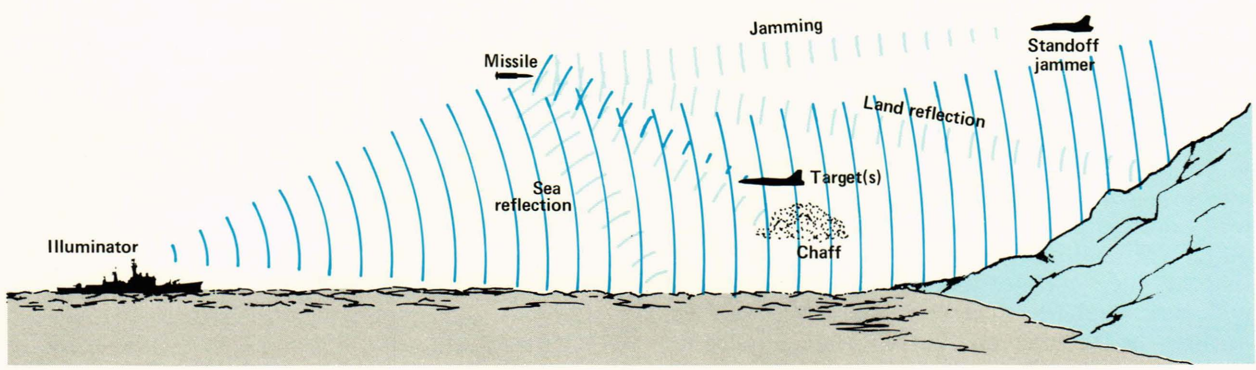


Figure 4 — Typical signals received by the missile in flight. Good steering information can usually be derived from either target-reflected energy or jamming energy from the target. Interfering signals, which can exceed the target skin return by many orders of magnitude, must be rejected. Interference derives from natural and man-made environments, both friendly and unfriendly.

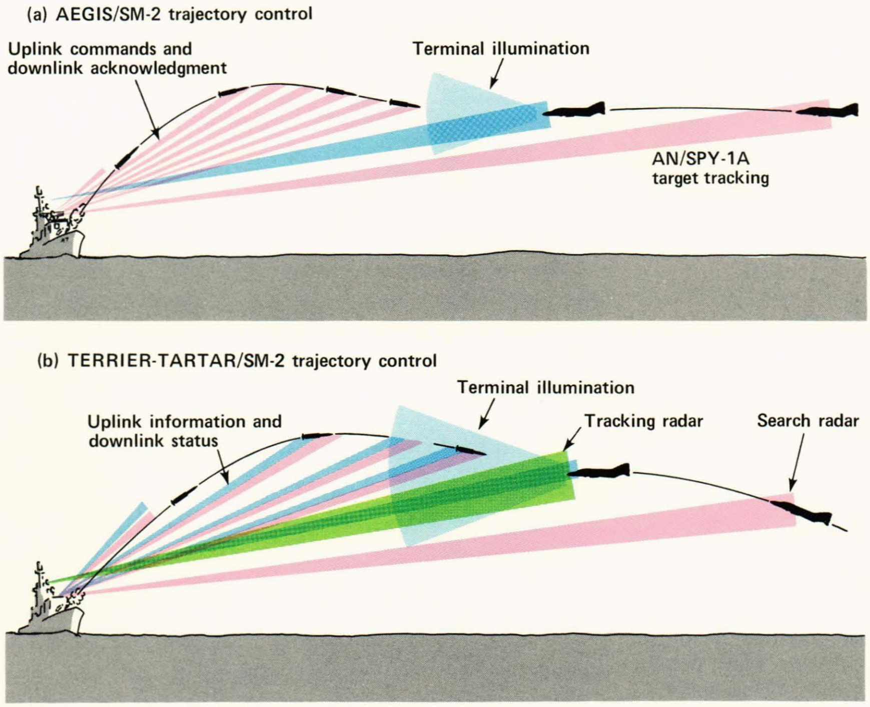


Figure 5 — SM-2 midcourse plus semiactive terminal guidance. In the AEGIS application (a), SM-2 is guided by the ship through the midcourse phase of flight. Uplink acceleration commands, which are acknowledged via the downlink, are converted into steering signals by the missile inertial reference unit. Terminal homing is commanded by uplink and can be delayed longer than in TERRIER or TARTAR because of greater midcourse accuracy.

In TERRIER and TARTAR Combat Systems (b), the SM-2 uses its inertial reference unit to guide itself to a point in space. New points are sent to the missile by the ship via uplink if course changes are required. Missile flight progress is monitored by means of downlink information. The missile switches to terminal homing at a predetermined time prior to intercept, subject to uplink revision.

tude reference system, transforming the uplink guidance commands in inertial coordinates to steering commands in missile body coordinates. At a predetermined time prior to intercept, the weapon system assigns an illuminator to the engagement to support the terminal phase. Shortly thereafter, the missile is told to search for the target based on updated seeker pointing and Doppler frequency information. The change from midcourse to terminal guidance, known as "handover," occurs following target acquisition by the missile seeker. The improvement in intercept capability relative to SM-1 is substantial in both downrange and crossrange because of the use of midcourse guidance.

TERRIER and TARTAR
Inertial Midcourse Guidance

In the TERRIER and TARTAR application, SM-2 uses inertial midcourse guidance for self-navigation, command guidance being impractical because these combat systems do not track the missile. Instead, using target data derived from a three-dimensional search radar, these ship systems direct the missile to a point in space, or to a succession of points in case the target changes course and/or speed (Fig. 5b). New guidance points, along with target position and velocity data, are communicated via the uplink as required. Missile information is downlinked, permitting the ship system to monitor flight progress. The midcourse guidance law is known as explicit guidance because the steering equations are explicit functions of the current and desired boundary conditions (position and velocity). The missile's knowledge of its own position and velocity is, of course, provided by the inertial reference unit.

As in AEGIS, at a predetermined time in the flight, the weapon system assigns an illuminator to support the terminal homing phase. Doppler frequency and angle information required for target acquisition by the missile seeker are computed from inertial reference unit and uplink data. Terminal handover, which follows acquisition, cannot be delayed as long as in AEGIS because of greater uncertainties in missile position and heading. Intercept coverage of TERRIER and TARTAR ships with SM-2 is also substantially increased relative to SM-1 against both incoming and crossing targets.

APL Contributions

Initially, APL contributed significantly to the development of SM-2 midcourse guidance in the TERRIER and TARTAR application by formulating the initial requirements and defining many of the basic concepts. This was a challenging undertaking, for not only was it to be the first tactical missile to use inertial midcourse guidance, but it had to be compatible with two existing shipboard systems. For a time, this work proceeded in parallel with the development of the new AEGIS Combat System. When the advantages of a common missile became apparent, APL helped define the resulting configuration through participation on a number of steering groups chartered by the Naval Sea Systems Command.

Subsequently, APL played a major role in connection with the development of both the AEGIS and TERRIER data links. From 1973 to 1976, extensive AEGIS link-compatibility tests were periodically conducted with APL participation. Concurrently, the Naval Sea Systems Command requested that APL design and evaluate an alternative AEGIS uplink receiver/decoder using improved signal processing concepts. The resulting design, successfully tested in 1977, was shown to be highly tolerant of expected variations in the uplink signal waveform. Subsequently, many of the features of the design were incorporated in the production version of the receiver/decoder. In addition, APL guided the development of the TERRIER and TARTAR uplink and downlink systems, performing much of the preliminary design work for the downlink system. Test and evaluation equipment for these systems was also designed and built at the Laboratory, culminating in final system integration testing at APL in 1976 prior to flight testing at sea.

STANDARD MISSILE-2 TERMINAL GUIDANCE

"Terminal guidance" refers to the self-navigation phase following midcourse guidance during which SM-2 homes on the target until intercept occurs and the missile warhead is detonated. A terminal guidance mode is necessary because midcourse guidance is not sufficiently accurate, even at short range, to consistently achieve miss distances less than the lethal radius of the warhead. The same terminal guidance equations are used in all SM-2 missile variants.

Many factors affect the success or failure of the missile during the terminal guidance phase. At the desired time of handover, seeker acquisition is the primary consideration. As intercept is approached, the kinematic capability of the missile (i.e., speed and maneuverability) relative to that of the target is critical. As might be expected, crossing and/or maneuvering targets tend to be more stressing than directly incoming, nonmaneuvering threats. Other factors having a major effect on guidance accuracy are an angle scintillation phenomenon known as target glint and, occasionally, severe fades in the target-reflected signal at a critical time prior to intercept. The extent to which the missile is not steering toward the actual intercept point at handover, i.e., the missile heading error, can also affect the final miss distance.

Figure 6 is a block diagram of the SM-2 terminal guidance loop. The characteristics of the signal received from the target (most importantly, angle of arrival) vary with target and missile motion. The seeker antenna receiving the signal is inertially stabilized to remove missile pitch and yaw motion. The missile receiver has two primary outputs, a line-of-sight angle measurement and a closing velocity (Doppler) measurement. The guidance computer uses these measurements to generate steering commands in accordance with a proportional navigation guidance law. In the same manner as during the midcourse guidance phase, the autopilot converts the guidance computer's electronic commands to missile tail deflections so as to alter the missile's trajectory. The result is lateral missile motion. With longitudinal motion provided by propulsion, the missile heads toward an intercept with the target.

The final phase of flight, known as the endgame, is characterized by a high-speed encounter with the target. Accurate timing of the warhead detonation is essential in this phase. When the missile and the target are close, a small radar aboard the missile, known as a target detection device or proximity fuze, senses the target's presence. A calculation is then performed to determine the optimum time to trigger warhead detonation. If the missile collides with the target before that time, a contact fuze detonates the warhead upon impact.

MONOPULSE RECEIVER DEVELOPMENT

As previously indicated, the purpose of the missile homing receiver is to provide an accurate measurement of the angle of arrival of the target signal with respect to the boresight axis of the seeker antenna. Three basic methods are commonly used in missile receivers to measure angle error: scan, interferometer, and monopulse[1] processing. As explained below, scanning receivers induce an amplitude variation on the received signal in order to derive a measurement of angle error. On the other hand, an interferometer measures the phase difference in the return signal as received at different antenna ports to obtain an estimate of the off-boresight angle. Monopulse receivers can be designed to make use of either amplitude or phase differences depending on the type of antenna

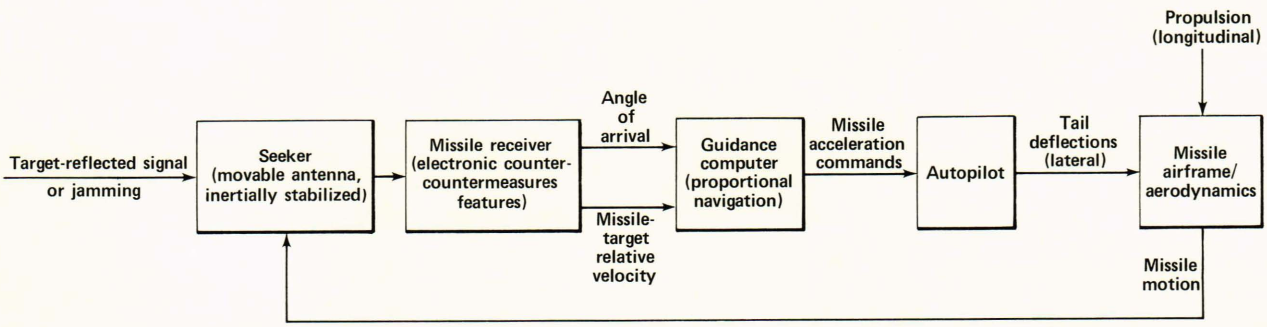


Figure 6 — Terminal guidance functional block diagram. STANDARD Missile terminal guidance is accomplished by processing an RF signal received from the target. The receiver determines the angle and relative velocity of the target while the guidance computer translates this information into steering commands. The autopilot adjusts the aerodynamic control surfaces to alter the missile's trajectory as required. Kinematic energy is provided by a solid rocket propulsion system.

PROPORTIONAL NAVIGATION

The problem of guiding a missile to an eventual near miss or collision with a target using only the observed motion of the missile-target line of sight has a number of potential solutions. Probably the most obvious is a simple pursuit course, in which the missile always flies directly toward the current target location. The disadvantage of this approach is the stringency of the missile maneuvers that are generally required as intercept is approached. A more favorable trajectory is a constant bearing course in which the missile leads the target, similar to the manner in which a projectile is traditionally fired at a moving object. If the missile flies a course that keeps the relative missile-target velocity aligned with the line of sight, a collision will always occur. If missile speed and target speed and course are constant, the missile trajectory is a straight line to the intercept point, as is shown in the illustration.

Proportional navigation is a steering law that is intended to yield a constant bearing course even if the target maneuvers. This is achieved by making the rate of change of the missile heading directly proportional to the rate of rotation of the line of sight. Ideally, this implies that the missile respond instantaneously to changes in the line-of-sight direction. In reality, there is some delay in returning to a constant bearing trajectory following a target maneuver because of finite missile responsiveness and filtering that is introduced to reduce the effects of noise.

In mathematical terms, the proportional navigation steering law is given by

$$\dot{\gamma}_M = N\dot{\sigma}, \qquad (1)$$

where $\dot{\gamma}_M$ is the rate of change of missile heading, $\dot{\sigma}$ is the rate of rotation of the line of sight, and N is a parameter known as the navigation ratio.

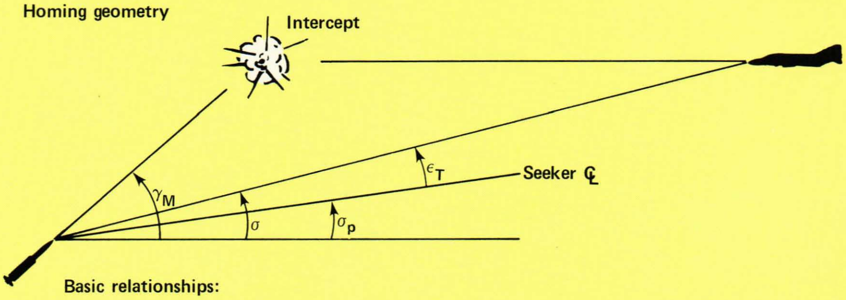
The navigation ratio governs the responsiveness of the missile in correcting for line-of-sight rotation. Theory indicates that its value should be proportional to the missile-target closing rate, i.e., the higher the closing rate, the more responsive the missile must be. With a continuous-wave-illumination homing system, a good estimate of the closing rate can frequently be derived from the Doppler frequency of the target return.

The angular rate of line-of-sight rotation, $\dot{\sigma}$, is measured by the missile seeker. The seeker antenna assembly, which is stabilized with respect to missile body motion, tracks the target. The tracking error, ϵ_m, derived from the signal processor, together with the antenna rotation rate, $\dot{\sigma}_p$, measured by antenna-mounted gyros, provides the information to compute the line-of-sight rate; i.e.,

$$\dot{\sigma} = \dot{\sigma}_p + \dot{\epsilon}_m . \qquad (2)$$

Computation of steering commands is performed by the missile guidance computer according to the above relationships. In addition to noise filters, compensations are usually introduced to account for such factors as variations in missile velocity and radome effects. Steering command limits are also imposed so that the missile maintains aerodynamic stability and does not exceed its structural capability.

Homing geometry



Basic relationships:

1. Steering equation for proportional navigation is $\dot{\gamma}_M = N\,\dot{\sigma}$.
2. From geometry, $\dot{\sigma} = \dot{\epsilon}_T + \dot{\sigma}_p$.
3. To obtain a measure of $\dot{\sigma}$, the signal processor provides ϵ_m ($\approx \epsilon_T$) and seeker-mounted rate gyros provide $\dot{\sigma}_p$.

employed. Phase-comparison monopulse receivers have become by far the most popular choice in modern missile receiver applications based on performance and hardware implementation considerations.

Until recently, scanning techniques were most common as a result of their relative simplicity. A scanning receiver measures angle by either mechanically or electronically nutating the antenna to form a conical pattern about the seeker axis (Fig. 7). The magnitude of the resulting amplitude modulation on the received signal can be shown to be proportional to the target off-boresight angle, while the phase is directly related to the polar orientation of the target. This information can be extracted by the receiver by processing the first harmonic of the scan sideband frequency. (In the frequency domain, the amplitude modulation of the received signal caused by the nutating antenna pattern is evidenced by sidebands displaced from the primary return signal at multiples or harmonics of the scan frequency.)

One of the major disadvantages of scan systems has been their inherent susceptibility to amplitude

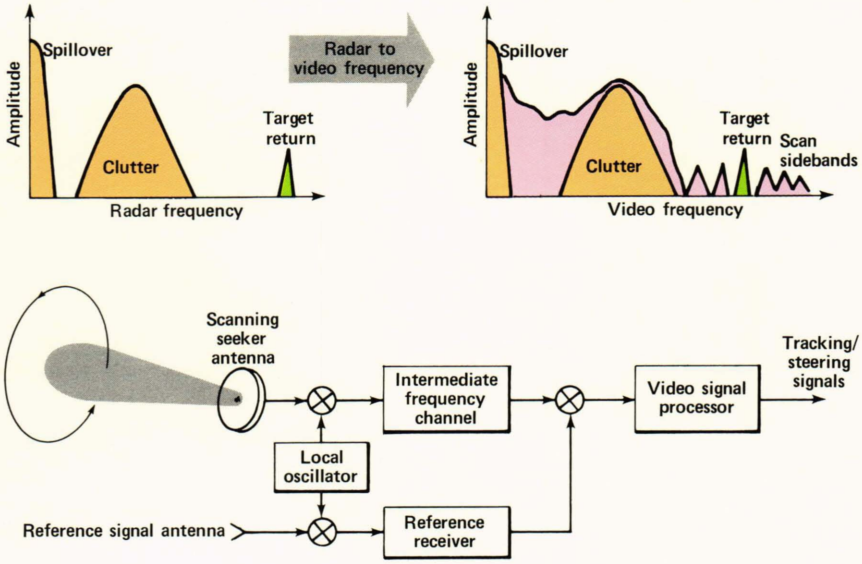


Figure 7 — Scanning receiver operation. Nutation of the scanning seeker antenna introduces an intentional amplitude modulation on the received signal. The modulation causes sidebands about each return, whether from the target or from clutter. Seeker angle error information is derived from the magnitude of the first scan sideband associated with the target signal. Scan sidebands associated with clutter can interfere with target detection and tracking.

modulation. While more modern scanning receivers have been developed using electronic techniques that are relatively immune, scan systems are basically at a disadvantage because they make a time-sequential determination of angle rather than a simultaneous measurement. A second disadvantage of scan processing is that the generation of scan sidebands can cause interference in the receiver. This is illustrated in Fig. 7, in which the scan sidebands of clutter overlap those of the desired target even though the fundamental signals are separated in Doppler frequency. Both monopulse and interferometer receivers avoid these disadvantages.

STANDARD Missile-2 Receiver Objectives

A primary objective in designing the SM-2 receiver was to take advantage of available technology to obtain the high degree of angle measurement accuracy afforded by one of the simultaneous signal processing techniques. Of course, it was recognized that this alone would not guarantee the desired level of performance in all of the signal environments considered possible for SM-2 operation. Consequently, a number of additional key features were defined at the outset to guide the design of the receiver and associated logic. As testing proceeded in conjunction with development, problems were found that invariably were traced back to a violation of the original basic principles. The performance of the final configuration, as demonstrated by extensive ground-based and flight tests, has since confirmed the soundness of the design approach. A brief discussion follows of the basic operation of the receiver, divided into angle error processing and Doppler processing functions.

Angle Error Measurement

SM-2 employs phase-comparison monopulse angle processing, enabling target direction to be determined on an instantaneous basis in two angular coordinates by comparing the signals received in appropriate lobes of the subdivided front seeker antenna. The directivity pattern for the SM-2 antenna consists of four parallel lobes, as shown in Fig. 8. By summing and differencing combinations of these four lobes, the Σ, $\Delta_{azimuth}$, and $\Delta_{elevation}$ signals are formed. Although these three signals contain all the necessary information for computing angle errors, they are not in a useful form and must be amplified, filtered, normalized, and translated to a lower frequency ("video") before final processing can be performed. In many respects, these operations are similar to those performed in ordinary radio sets.

Following the microwave arithmetic, the information needed for computing the angle error is contained in the amplitude and sign of each of the Δ channel signals relative to the Σ signal. Although separate channels might conceivably have been maintained for each of these signals until the final angle error computation was performed, the approach taken was to combine the Σ signal with each of the Δ signals in phase quadrature. Since the Δ signals are typically small compared to the Σ signal, the phase quadrature combination is approximately equal in amplitude to the Σ signal and has a phase shift relative to the Σ signal that is proportional to the angle error. The new signals are multiplexed through a common limiting amplifier that normalizes the amplitudes but preserves the phase relationships. Following normalization, the signals are demultiplexed, filtered, and phase compared to reproduce the desired angle errors for use in pointing the seeker and providing missile guidance information. This implementation requires less hardware than the separate channel approach, and also facilitates the preservation of relative gain and phase between the Σ and Δ signals.

Doppler Processing

When several competing signals are received, the one with the largest amplitude will inherently be pre-

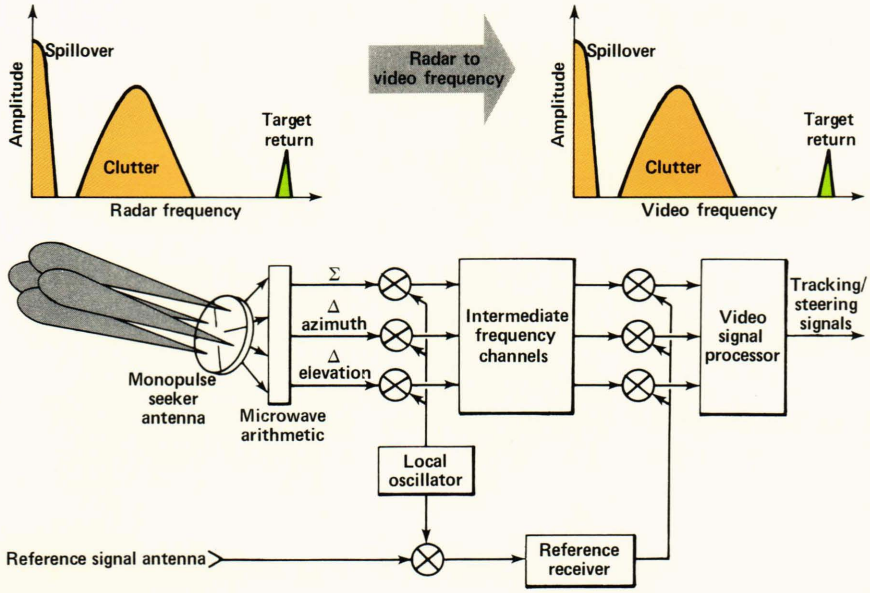


Figure 8 — Monopulse receiver operation. Angle error information is contained in the relative magnitudes of the Σ and Δ signals formed by summing and differencing the signals received by the four symmetrically offset lobes of the monopulse antenna. This simultaneous measurement approach circumvents the amplitude modulation in time-sequential measurement (scanning) receivers, resulting in a significant reduction in Doppler-band interference.

ferred. Therefore, in most signal environments, the desired target signal must be isolated from unwanted signals that may be many orders of magnitude larger. In a continuous-wave semiactive system, this is usually accomplished by taking advantage of the fact that the various signals received will possess different Doppler frequencies because of velocity differences (Fig. 8). Spillover, the signal resulting from energy that enters both the front and reference receivers via the direct path from the illuminator to the missile, will have a zero Doppler frequency. Chaff and clutter have near zero velocity relative to the illuminator, so their Doppler frequency is primarily dependent upon the missile velocity. Relative to stationary objects, the Doppler frequency of an incoming target will be higher, that of a crossing target will be approximately the same, and that of an outgoing target will be lower. Although it is not shown, inherent receiver noise is present throughout the Doppler spectrum. In addition, jamming may occur selectively or at all frequencies.

To acquire a desired target signal, a technique similar to that used in tuning an FM radio receiver is used. This consists of searching the spectrum in the neighborhood of the desired signal until it is located. At that time, automatic frequency control is used to maintain frequency tracking. In the missile receiver, the search is programmed and the switch to frequency tracking is automatic, based on the results of a signal bandwidth, or coherency, test. A comparison of the spectra in Figs. 7 and 8 indicates that tracking the target signal with a monopulse receiver in a dynamic situation should be easier because it is not contaminated with scan sidebands.

APL Contributions

APL contributed to the design and development of the SM-2 monopulse receiver by defining the primary requirements, formulating techniques in close cooperation with General Dynamics/Pomona personnel for achieving the specified performance, performing trade-off studies where alternative approaches were apparent, and conducting a comprehensive test program on the final configuration. Some early APL contributions to the design were made with the aid of a simulator that greatly facilitated the optimizing of circuit parameters over a variety of threat environments. Subsequently, the first closed-loop homing tests with actual guidance hardware were made at APL. Throughout the development program, strict adherence was paid to the fundamental principles defined at the outset despite occasional pressures to do otherwise. The resulting performance, as demonstrated by nearly 100 flight tests, has confirmed both the soundness of the approach and the initial predictions of the APL and General Dynamics/Pomona designers.

TEST AND EVALUATION

The SM-2 guidance system was subjected to an extensive series of ground-based and flight tests throughout its development, with significant APL participation. In retrospect, the Naval Sea Systems Command's "build-a-little, test-a-little" philosophy was crucial to the success of the development process. As soon as guidance hardware was made available to APL, emphasis shifted from the simulator to testing in the APL Guidance System Evaluation Laboratory. Subsequently, flight tests were conducted, including instrumented test-range firings and tactical system evaluations at sea.

Guidance System Evaluation Laboratory

The Guidance System Evaluation Laboratory (GSEL) has been used continuously for testing guidance hardware since it was established in 1965. Upgraded substantially in 1980 to better support SM-2 development, the facility consists of an anechoic test chamber that houses the guidance section to be tested, generating equipment to reproduce electromagnetic signal environments representative of actual flights, and a hybrid computer system to control test conditions and simulate the dynamic interactions of the missile and the target. Tests can be performed to simulate a wide variety of threat situations, including those involving countermeasures.[2]

SM-2 testing in GSEL began in 1975 with an evaluation of a prototype SM-2 guidance section. Follow-on evaluations were performed using both preproduction and production units. The primary objectives of those tests were to conduct an in-depth evaluation of the guidance system design and to determine guidance accuracy in intercepting both known and projected threats. In the early stages of development, the first objective tended to dominate as design shortcomings were invariably uncovered. Working closely with the missile Design Agent, solutions to each problem involving either hardware or computer program modifications, or both, were developed and verified. After the design was reasonably firm, a comprehensive series of tests was conducted to assess guidance accuracy in terms of miss distance. That evaluation included tests involving a broad spectrum of threats. The overall conclusion of the test program was that the design objectives of SM-2 had been achieved.

Another important facet of the GSEL test effort was in support of flight test activities. The conditions to be employed in planned flight tests were simulated to provide performance predictions and to ensure that the tests provided a significant demonstration of capability with a reasonable margin for success. Occasionally, unexpected phenomena were encountered in a firing with a suspected link to the signal environment. Missile hardware would then be tested in GSEL over a range of environmental conditions bracketing those of the flight. Such examinations often led to a better understanding of missile operation.

Flight Testing

The initial flight tests of SM-2 were conducted at the White Sands Missile Range in New Mexico. While White Sands is part of the National Range System operated by the U. S. Army, the Navy as a tenant has access to the range communication, tracking, and support facilities necessary for missile testing. In addition, a weapon control system and launcher have been installed at the Navy installation (USS DESERT SHIP) so that the system-to-missile interface is functionally equivalent to an actual shipboard system.

SM-2 test firings were conducted with a Navy crew supported by civilian contractors (Fig. 9). APL maintains a close working relationship through a field office and a resident engineer. In addition, APL heads the Computer Programming Committee that develops Weapon Control System computer programs to support individual flight test scenarios. APL is also represented on the Test Coordination Panel and participates in post-flight analyses.

After completion of the engineering development flight test phase at White Sands, combat system tests were conducted in an operational shipboard environment. From a missile standpoint, at-sea testing enables modes of operation to be evaluated that are beyond the capabilities of White Sands, partly because of range safety considerations. AEGIS at-sea testing was conducted in USS NORTON SOUND (AVM-1) in 1976, 1977, and 1978; TERRIER testing was conducted in USS WAINWRIGHT (CG-28) in 1976 and in USS MAHAN (DDG-42) in 1978 and 1979. Preceding shipboard testing, the TERRIER/SM-2 Combat System was assembled and tested at the APL Land Based Test Site. After successful completion of this evaluation, the equipment was transferred to the firing ship. During the initial phases of this test program, APL advisors assisted in the training of Navy personnel.

Based on the successful SM-2 flight test program in USS MAHAN, the TERRIER Combat System with the SM-2 missile was approved for service use on October 2, 1979, by the Chief of Naval Operations. AEGIS with SM-2 will become operational when the first AEGIS ship, TICONDEROGA (CG-47), is deployed.

STANDARD MISSILE-2 UPGRADE PROGRAM

With the initial version of the SM-2 in production, attention has focused on extending its guidance system's ability to counter the growing threat of high-speed, high-altitude, antiship missiles launched from aircraft. Taking advantage of recent advances in digital processing techniques, the SM-2 guidance section has been provided with a fast Fourier transform digital signal processor. This processor is functionally equivalent to a set of contiguous analog Doppler filters, each having a small bandwidth. The objective is to enhance acquisition and tracking of returns from

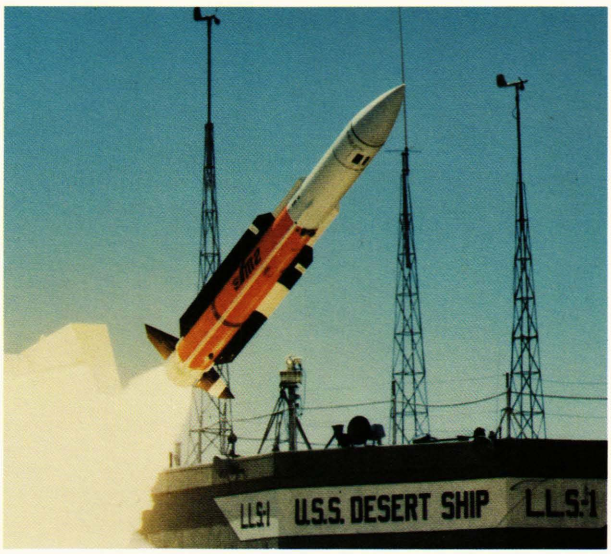


Figure 9 — Launch of an AEGIS SM-2 flight test round at the USS DESERT SHIP at White Sands Missile Range.

targets in the presence of obscuring jamming noise. APL's most significant contribution to the digital signal processor design was the development of a digital automatic gain control that provides the processor with the ability to handle signals of widely varying amplitudes.

In addition to signal processing improvements, missile propulsion has been increased to provide the kinematic capability for successful high altitude intercepts. This, in turn, led to the need for radome accommodations to compensate for the effects of increased aerodynamic heating. APL again played a key role, in conjunction with General Dynamics/Pomona, in defining the required changes. The resulting improved version of SM-2, designated Block II, is currently in engineering development.

ADVANCED GUIDANCE POSSIBILITIES

The feasibility of multiple guidance modes is currently being examined in an exploratory development context with potential applicability to a future STANDARD Missile. Homing modes being considered, in addition to semiactive, include active (in which each missile carries its own transmitter), infrared, and wideband home-on-jam. Some of the more attractive multimode combinations include semiactive terminal supplemented by either active or infrared, active terminal supplemented by infrared, and these plus wideband home-on-jam.

Currently, several programs have been initiated to demonstrate the technology required for alternate or supplemental guidance modes. Examples include development of high power, active transmitters; multiband antenna systems; and infrared domes for high speed flight. Physical integration of multiple sensors into a guidance package and definition of multimode guidance system control logic are also being addressed.

NOTES

[1]The word "monopulse" originally referred to a radar system that required a single pulse to measure the target off-boresight angle. When applied to a continuous-wave receiver, it implies that angle error is measured by simultaneously comparing the return signal as it is received in various sections of a subdivided antenna.

[2]For further information on the Guidance System Evaluation Laboratory, see W. M. Gray and R. W. Witte, "Guidance System Evaluation Laboratory," *Johns Hopkins APL Tech. Dig.* **1**, 144-147 (1980).