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FLEET AIR DEFENSE: COUNTERMEASURES

Countermeasures have played a major part in the Applied Physics Laboratory's work since its inception. Our countermeasures activities have been distinctive: while attention has been given to seeking design concepts that would make air defense systems immune to threat countermeasures, simultaneous attention has focused on conceptual countermeasures that could be used against such systems. This response/counterresponse adversarial philosophy has created a heightened understanding of fundamental countermeasure issues and, accordingly, has significantly contributed to the development of numerous Department of Defense weapon systems.

INTRODUCTION

Webster's defines countermeasure as "a measure or an action taken in opposition or retaliation." Conversely, a countercountermeasure can be defined as an action taken in opposition to a countermeasure. In warfare, a countermeasure can take many forms; for example, a defending aircraft might execute a maneuver to elude an approaching anti-aircraft warfare (AAW) missile, or some form of electronic jamming might be used to defeat the opposition's radars and AAW missile guidance. Jamming is typically defined as an electronic countermeasure (ECM). Conversely, a characteristic of the victim system designed to counter the jamming, for example, a home-on-jammer (HOJ) mode, is typically defined as an electronic countercountermeasure (ECCM). To extend these definitions, ECM and ECCM have been defined as a subset of what is known as electronic warfare. Since a significant part of APL's countermeasure work throughout the years has been devoted to electronic warfare, the major focus of this article is how it has affected and continues to influence the development of the fleet's air defense systems.

During the past fifty years, electronic warfare has appeared as an escalating contest between opposing ECM and ECCM forces. During the early years, ECM and ECCM designs were relatively simple. Active jammers consisted of unmodulated noise, which was used to conceal the defended threat, obliterate communications, and so on. The ECCM in the radars and missiles could do little more than track or home on the noise. Eventually the electronic warfare contest intensified. Simply, those concerned with jamming would analyze the capabilities of their victim systems and would develop ECM to defeat them. The designers of the victim systems, in turn, examined the newest jamming threat to their systems and then developed new ECCM features to defeat the jamming. In essence, the electronic warfare challenge was to force the opposing side to a point where it could not win or simply found it undesirable to go any further. This contest continues today.

RESPONSIVE THREAT

Early on, two problems pertaining to the electronic warfare capabilities of DoD weapon systems became evident. First, ECCM was not addressed until late in the system design process. Second, the action followed by counteraction between the opposing electronic warfare players resulted in inherent delays between the time a threat was observed and the time a counter to that threat could be fielded. Thus, the ECCM designers were continually "shooting behind the rabbit." Both of these problems necessitated quick "band-aid fixes," which frequently had to be designed around existing hardware. This, in turn, resulted in less-than-fundamental solutions and compromises in performance; the ECCM responses came too late and often with limited effectiveness.

The Laboratory's approaches to both problems have differed from those commonly practiced throughout the DoD. First, countermeasures have been considered by APL at the very outset of system design. For example, Figure 1 shows an early organizational chart, scribbled by Merle Tuve on his desk pad in April 1942, which included a task to address jamming.

Second, APL has embraced a "responsive threat" philosophy, which was summarized by Alvin R. Eaton (personal communication, 1988): A major system design will lead, in a generally predictable way, to dynamic changes in the threat, and will impel the adversary to act responsively and quickly as information becomes available to develop countermeasures and countertactics consistent with its state of technology and philosophy of tactical operations. The system designer must then assess what an informed enemy might reasonably do, within the limitations of his resources, to counter the system. A key word here is "informed." One must assume that significant system design and performance characteristics will be known well before the system is fielded. This knowledge can come from numerous sources, including technical journals, the open literature, technology transfer through open commerce, field testing, and so on.

The proper reaction to a responsive threat, in APL's opinion, is that the system designer should, within budgetary and time constraints, seek fundamentalal design solutions that will make the performance of the system as independent as possible of what an adversary might do in the future. Where fundamental solutions may not be achievable, the use of complementary modes and

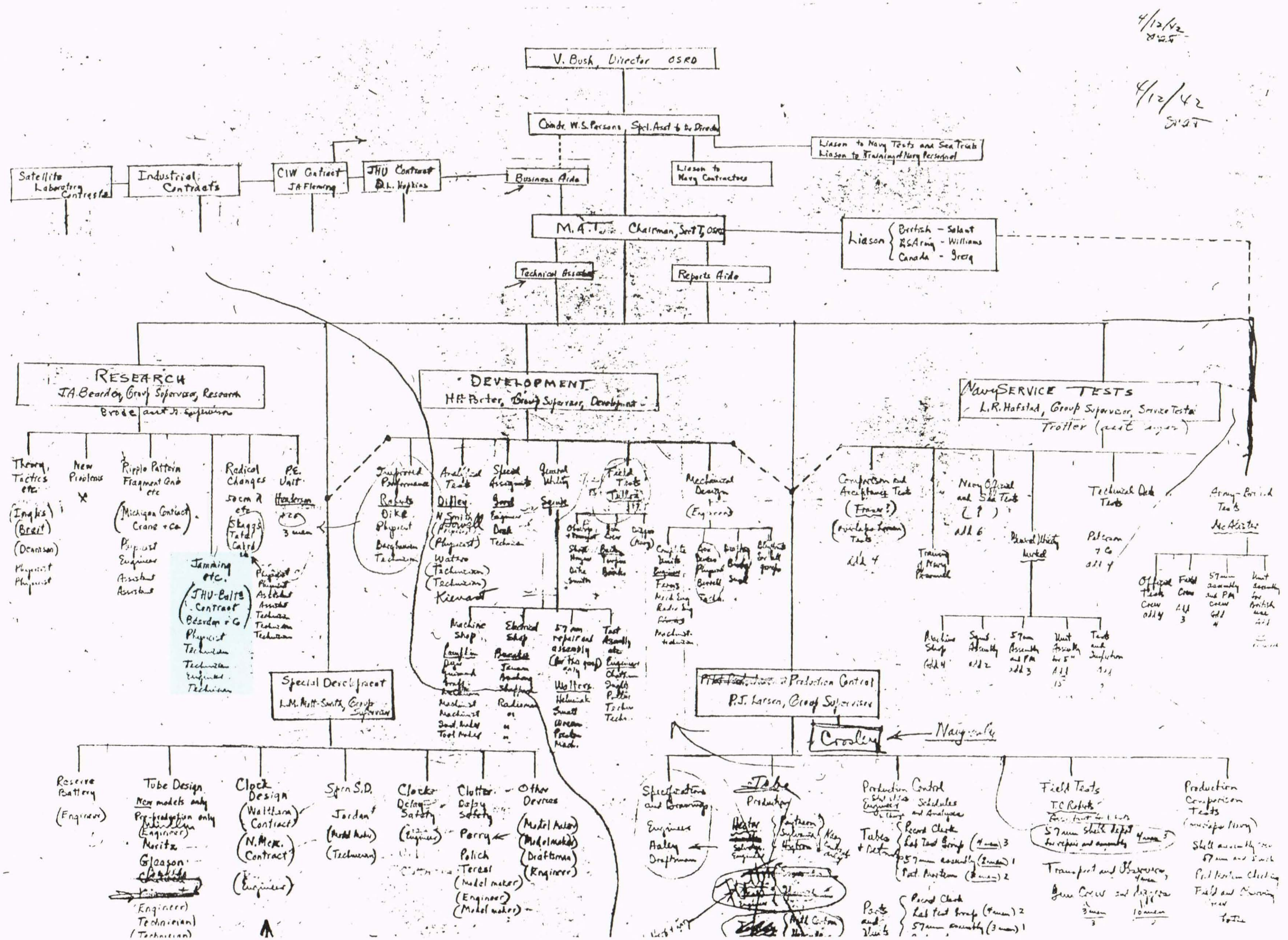

Figure 1. The importance of countermeasures has been recognized by APL throughout its fifty-year history. One of the first organizational charts for the Laboratory, scribbled by Merle Tuve on his desk pad in 1942, included a task to address jamming of the proximity fuze.

systems should be employed to complicate the adversary's countermeasures and tactics to a point where he would find them too costly or too risky to use.

While APL was pursuing the responsive threat methodology and philosophy, the DoD eventually adopted a threat assessment process that concentrated on the projection of a "technologically feasible threat." That was a move in the right direction, but it still missed the responsive threat need. The projection of future threats solely on the basis of the feasibility of technological development and application is dangerous and can lead to wrong answers. A recent DoD directive,[1] however, promises to correct such a risk by addressing a "reactive threat," which essentially reflects APL's responsive threat methodology and philosophy.

EARLY YEARS

Following the development of the proximity fuze in the 1940s, APL's principal task was the development of a long-range supersonic guided missile for fleet defense. That effort led to the Talos missile, with spin-offs that became Terrier, Tartar, and, eventually, the Standard Missile. Accordingly, much ECCM work during the 1940s and 1950s was associated with the guided missile efforts. The shipboard equipment during those years consisted mainly of inherited World War II surveillance and gun control radars. The shipboard systems did eventually receive major attention when it was recognized that the entire platform had to be addressed, not just the weapon.

The Talos guidance consisted of a midcourse phase, which was under control of the ship, followed by a relatively short terminal phase in which the missile used the radar signal reflected from the target for homing (i.e., semiactive homing). The first Terrier was a relatively short-range missile, with guidance solely under the control of the ship. Subsequent Terriers, Tartars, and the Standard Missile Type 1 (SM-1) used semiactive homing guidance for the entire missile flight (i.e., "home-all-way").

Early in the electronic warfare contest, APL focused on the countermeasures issues associated with the missile's homing guidance. In general, we recognized that if an attacking aircraft wanted to use jamming to attack the missile's command or midcourse phase, the most effective action would be to jam the systems aboard the ship; a ship would gain little or nothing by launching an AAW missile to intercept a target if the location of that target was not known. If the aircraft needed to defend itself against an AAW missile that had been successfully launched toward it, then the most effective countermeasure would probably be to attack the missile's homing guidance.

The first type of active ECM that the missile designers had to deal with was simple wideband noise jamming. The early use of radars in World War II showed that if a jammer could radiate a noise-like signal that would appear in the passband of the victim radar, it could prevent the radar operator from seeing the defended aircraft. With the emergence of guided missiles, it was obvious that a homing missile would have similar problems. The response to this relatively simple, continuous noise jamming was to detect the presence of the jamming and use that signal for missile homing guidance, that is, an HOJ mode. Similar capabilities also appeared in radars and have typically been known as passive angle track. The early AAW missiles, with an HOJ mode, performed well against that simple noise jamming countermeasure.

Sequential Lobing Systems

Inherent electronic warfare weaknesses in those early missiles existed, however, which were rooted in the use

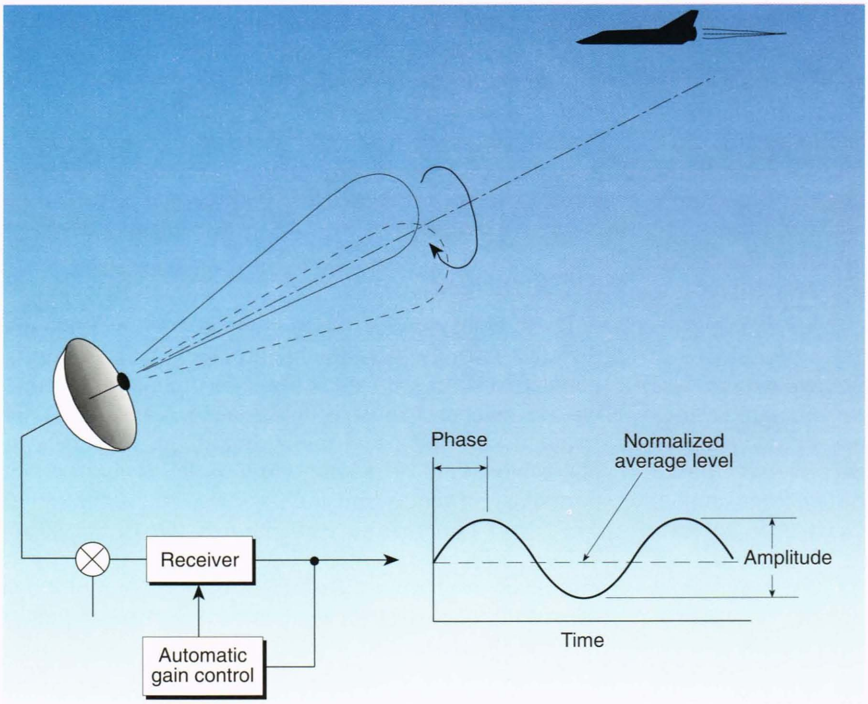

Figure 2. The early anti-aircraft warfare guided missiles, and most target tracking radars, used sequential lobing techniques (e.g., conical scan) for tracking the targets in angle. The antenna's main beam was rotated about the target's approximate position. The signal at the output of the antenna system was amplitude-modulated at the scan rate. The depth and phase of this modulation provided the polar coordinates of the target's angular position. The principal electronic warfare issue with these systems was the need to preserve the amplitude–time and phase–time history of the signal out of the antenna. Numerous jammer modulations existed that could destroy the integrity of the signal, and thus defeat the system.

of sequential lobing for tracking the target in angle. A conical scan system, shown in Figure 2, is an example of sequential lobing. Here, the missile antenna beam is rotated about the angular position of the target. The output of the antenna is an amplitude-modulated signal. The amplitude of the modulation is proportional to the target's angular displacement from the scan axis, and the phase of the modulation is related to the target's polar orientation (i.e., whether the target is up, down, left, right, and so on). This type of angle measurement system was used in homing Terrier, Tartar, and SM-1. Partially because of its ramjet airframe characteristics, Talos used a body-fixed scanning-phase interferometer system, wherein the angular motion of the target was obtained using the phase difference of the target signal as received via antenna pairs mounted firmly to the outer part of the missile airframe. The principal electronic warfare characteristic of both of these systems was the amplitude–time and/or phase–time history dependence of the signal out of the antenna system, which was something that a jammer could affect. Thus, many options were available by which the jammer could be modulated (e.g., amplitude modulation at or near the scan frequency), thereby preventing satisfactory HOJ guidance.

Missile designers faced additional problems, some directly related to the sequential lobing systems and some to the relatively slow signal processing common during the 1940s and 1950s. For example, the automatic gain control (AGC) of the receiver had to be slow to preserve the scan modulation. A blinking jammer with a blink repetition rate near the AGC time constant could alternately drive the output of the receiver into and out of saturation. In some systems, HOJ processing was accomplished via circuits that were separate from those used for normal target acquisition and track. The time required to establish target acquisition, target track, jammer acquisition, and jammer track was too long for the electronic warfare game. Thus, the jammers could be turned on and off at rates that could leave the missile with only limited guidance data or even no guidance at all. Similar problems also plagued those involved with radar.

Missile designers tried to work around these early electronic warfare problems by devising distinctively tailored logic fixes, each created to counter some specific jammer modulation. That proved to be an exercise in futility and was doomed to failure. In fact, many of those ECCM fixes frequently created more problems than they solved. At this point, the jammer designer was clearly the winner.

Combined Tactics

By the late 1950s and early 1960s, awareness was growing that other potentially effective countermeasures would involve several different types of actions employed in concert; some actions, ineffective when used alone, could be devastating if used together. For example, Figure 3 shows the relative miss distance of an AAW missile against a maneuvering target. Two curves are presented: one shows guidance accuracy when a target maneuver (e.g., a weave) is executed with the jammer turned off; the other shows the effects of combining the jamming and the maneuver. The jammer modulation here was not optimized to prevent an acceptable intercept if the jammer was used alone. The jammer could, however, make the missile guidance sluggish, as would occur if the jammer forced the missile to alternately switch between normal target acquisition and HOJ, resulting in repeated periods of no guidance information. Once the jammer could make the missile guidance sluggish, the maneuver could defeat the missile.

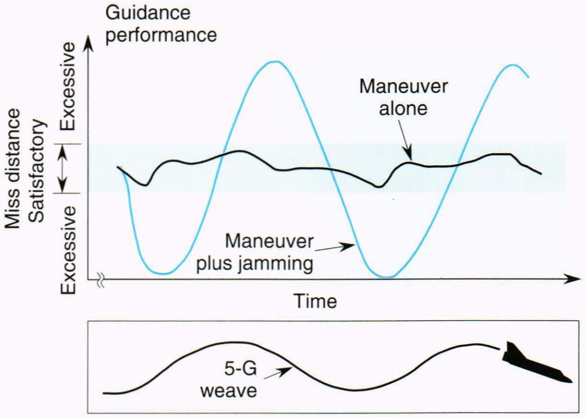

Figure 3. Some countermeasures, when used singularly, are ineffective, but when used in concert, they may be very effective. This figure shows how the combination of jamming and a target maneuver could defeat one of the Navy's early air defense missiles. The upper portion indicates guidance performance as a function of the target maneuver shown in the lower portion. The black curve indicates guidance accuracy, assuming a maneuver without jamming; the blue curve indicates guidance accuracy when the maneuver is accompanied with jamming.

An operational example of the benefits of combining a maneuver with self-protection jamming occurred during the Vietnam conflict. Early in that war, the United States suffered unacceptable aircraft losses to a Vietnamese air defense missile system. The DoD asked the Laboratory to see if a countermeasure could be devised that would nullify the effectiveness of that weapon system. The countermeasure developed by APL consisted of jamming, which would slow the response of the air defense system and then defeat the AAW missile through the execution of a specifically defined maneuver. The countermeasure was successful; it reduced the effectiveness of the Vietnamese air defense system to near zero.

MONOPULSE

By the early 1960s, Billy Dobbins and Wilbur Goss directed, with the Navy's concurrence, that an effort be pursued to make the Talos missile the winner in any one-on-one contest against a target using a self-protection jammer with any conceivable amplitude, frequency, or phase modulation (i.e., any jammer that would prevent normal target acquisition and track would lose the game). The effort commenced even though the future of the Talos missile was in doubt because of the Typhon Program then in progress. Regardless of the future of Talos, the results of that effort were believed to be of benefit to other air defense missile programs.

Following the lessons learned using sequential lobing, it was obvious that the new guidance system had to be "monopulse." The term as generally used today describes what in reality is simultaneous lobe comparison. In a simultaneous lobe comparison system, the target (or jammer) signal is processed simultaneously from multiple antenna beams. Target angle data can be derived without the time-dependence factor, which was the electronic warfare problem fundamental to the sequential lobing systems. For example, with a pulse radar, target angle can be determined by processing a single pulse, hence the term monopulse. The process is equally applicable to continuous wave systems, however.

Interestingly, a monopulse system was not new to the Talos missile. The original Talos homing guidance (which, incidentally, was a pulse system) was based on work done independently and almost simultaneously in the 1940s by the Defense Research Laboratory at the University of Texas under contract from APL and by MIT. Some of the MIT work resulted in several guidance receiver configurations that had all the characteristics of a simultaneous lobe comparison system; they contained separate intermediate frequency channels for processing the signals from each antenna. The designs were unwieldy from a packaging perspective, however; one of the MIT systems contained ninety-eight vacuum tubes.[2] Because of those packaging problems, a simpler scanning (sequential lobing) interferometer system was selected for the original homing Talos.

The incorporation of a simultaneous lobe comparison receiver in Talos (Fig. 4) became possible in the early 1960s as a result of the emerging solid-state technology. The Laboratory also recognized that simultaneous lobe comparison, per se, was not sufficient—other aspects of the design had to be addressed. Thus, a set of fundamental design principles was identified that, if adhered to, would enable any AAW homing missile to win the contest with any self-protection jammer. In addition, this and subsequent efforts showed the if any of the principles were violated, a countermeasure probably existed to defeat the missile. Those design principles have since been implemented in Standard Missile as well as other U.S. surface and air-launched AAW missiles.

The performance of the first monopulse missile against a jamming target is indicated by the miss distance data shown in Figure 5. These data were obtained (1) from extensive laboratory hardware-in-loop testing conducted over several years by the Countermeasure Group at the Naval Ordnance Laboratory, Corona, California, (2) from live missile firings against jamming targets, and then (3), for reference, from Talos firings against nonjamming targets. For consistency with the monopulse seeker objectives, much of the evaluation involved the use of newly assembled jamming equipment that could generate new jamming techniques and waveforms that were based on detailed knowledge of the system. Also, the majority of the data points were collected with jammer parameters most stressing to the missile, for example, those causing extensive guidance switching between the target echo and the jammer. Today, even with the increasingly sophisticated jammer technology available, no known jammer modulation (amplitude, frequency, phase, or combi-

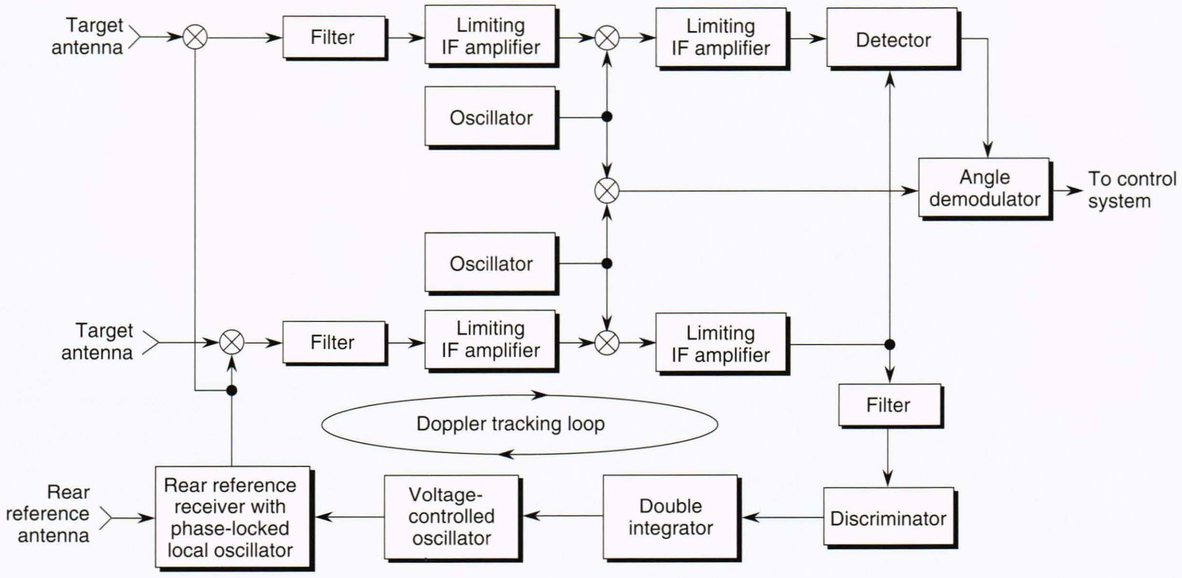

Figure 4. The fundamental solution to the countermeasure problems rooted in the sequential lobing systems rested with the transition to simultaneous lobe comparison (monopulse). The fleet's first monopulse missile was the Talos RIM-8J. The monopulse seeker was a refinement of the Talos inverse continuous wave Doppler seeker developed by APL in the 1950s. The target and/or jammer signals were processed through a four-channel receiver (two for each guidance plane; only one channel shown). The intermediate frequency (IF) amplifiers were hard-limited on receiver noise (i.e., no automatic gain control). The home-on-jammer mode employed the same narrow bandwidth and angle-processing circuits used for tracking the target echo. The target acquisition circuits were designed to ensure minimal time for reacquisition.

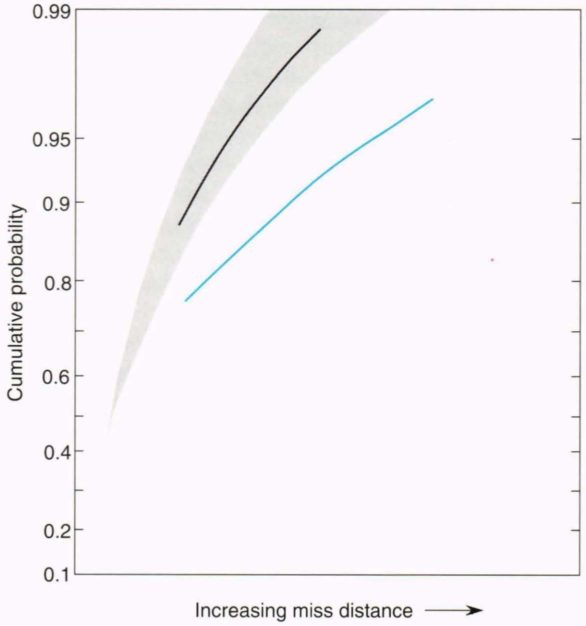

Figure 5. Electronic countercountermeasure design fundamentals established during the Talos monopulse effort showed that a homing missile can perform very well against a target using virtually any self-protection electronic countermeasure (ECM) designed to attack the missile seeker's receiver, signal processing, or logic. The Talos performance against the jamming targets was superior to that against the nonjamming targets. The jammers literally became beacons for the missile to home on. (Shaded area, ECM test data from the Naval Ordnance Laboratory, Corona, Calif.; black curve, live missile firings with ECM; blue curve, live missile firings without ECM.)

nations thereof) has surfaced, or is projected in the future, that would have defeated that guidance system, even if the jamming were accompanied with a target maneuver.

One cannot imply, however, that all subsequent AAW missiles will perform as discussed above and shown in Figure 5. For various reasons, some missile designs have been better than others. The important point at this stage in the electronic warfare contest was that fundamental solutions to the conventional self-protection jammer countermeasures had been defined, and the missile was clearly the winner. Any attacker attempting to defeat one of the fleet's air defense missiles today by using the types of self-protection jamming so effective against the earlier missiles would do so with extreme risk.

For shipboard radars, the monopulse efforts took two paths. First, by the late 1950s, the importance of addressing the entire air defense task as an integrated system led to the Typhon Program. Central to the Typhon system was a unique concept of a multifunctional phased-array radar conceived by John B. Garrison (see the article by Gussow and Prettyman, this issue). The radar could simultaneously perform the surveillance task, track multiple targets, support missile guidance, and provide a high level of resistance to ECM. Both the radar and the accompanying Typhon missiles were to be monopulse. The SPY-1 radar currently deployed on the U.S. Navy's Aegis ships had its roots in that pioneering multifunctional, phased-array radar work.

Second, electronic warfare problems similar to those experienced by the missile designers during the 1950s were also evident in existing Talos, Terrier, and Tartar radars. The Laboratory, which had not been heavily involved with shipboard radars during the early years, finally became very active in the mid-1960s.

Monopulse was eventually incorporated in all existing fire control radars by the mid-1980s. (Talos dropped out of the picture in the mid-1970s.) The existence of monopulse by itself, however, was not sufficient for the radars to play a meaningful role in the electronic warfare game. Numerous antijammer features were subsequently incorporated, including the merging of X-band continuous-wave Doppler and C-band pulse-Doppler tracking systems. To support the radar improvement programs, APL assembled and operated a land-based test site, which contained the major elements of the Terrier combat system, including both the search and fire control radars. Most upgrades to the Terrier fire control radar and modifications to it for support of the Extended Range Standard Missile-2 originated or were evaluated in that test site.

OFF–BOARD COUNTERMEASURES

Although the missiles and radars had essentially won the one-on-one contest with targets using conventional on-board self-protection countermeasures, APL recognized that the electronic warfare contest would eventually involve false targets that reside, or appear to reside, off the defended target. These countermeasures generally fall into two groupings—one for "self-protection," and the other for "support," wherein the countermeasure is used to protect some other aircraft or missile.

Self-Protection Off-Board Countermeasures

The off-board countermeasures used for self-protection generally entail the deployment by the defending aircraft or ship of devices (decoys) that will confuse the attacker's surveillance and targeting systems. For example, Figure 6 shows a radar display of eleven ships and two passive decoys. The decoys were developed by APL in the 1970s as a possible element of fleet defense. Another application of this countermeasure is for an attacking aircraft to eject chaff and/or other small decoys (e.g., flares, jammers) to force the opposition's fire control radars and missile guidance to transfer track away from the defended target and to the decoys. The AAW missiles would then home on the decoy(s), leaving the defended aircraft free to continue its mission (Fig. 7).

One APL effort to address off-board countermeasures was to provide the fire control radars immunity to chaff. The first antichaff feature involved a technique in which only the leading edge of the target video (closest in range) is used for tracking (i.e., leading edge track). (Chaff, because of its rapid deceleration to near-zero velocity immediately after deployment, typically appears toward the trailing edge or aft of the desired target signal.) The Laboratory also developed continuous-wave Doppler acquisition and track systems and added them to some of the radars. (Continuous-wave Doppler homing systems already existed in the missiles.) With these modifications and other features associated with enhanced range reso-

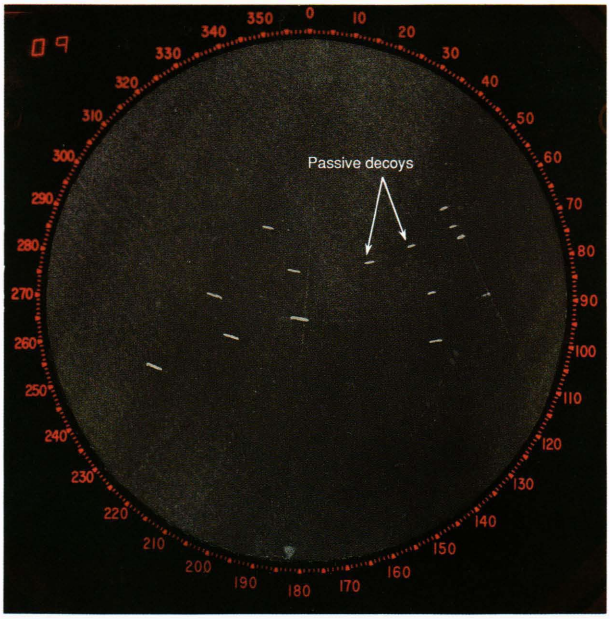

Figure 6. With solutions to the one-on-one countermeasure problems well understood by the mid-1960s, increased attention was given to "off-board" countermeasures (i.e., those presenting false targets that either reside or appear to reside off the defended target). This radar presentation shows how passive decoys can resemble combatant ships. Decoys can be used to complicate the attacker's targeting problems and provide low-cost expendable sources for antiship missiles to home on.

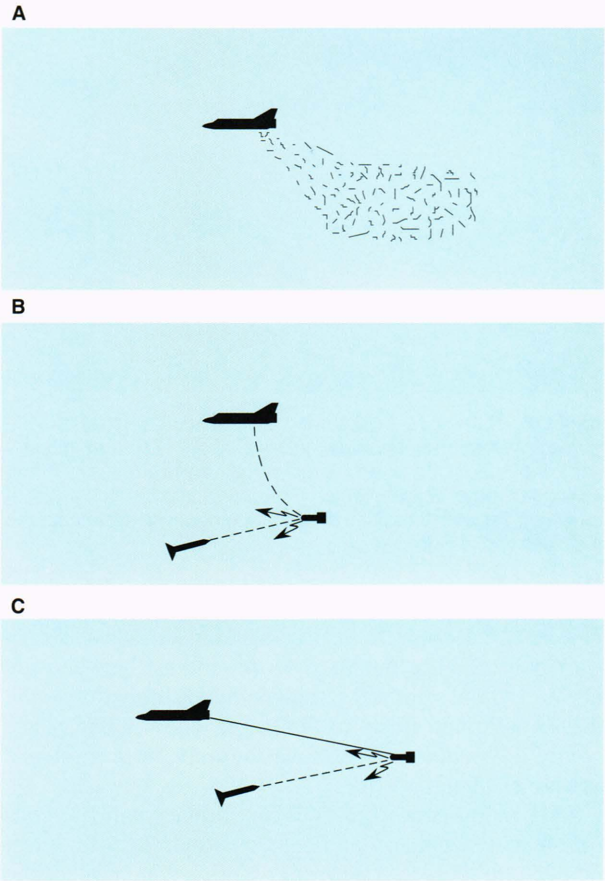

Figure 7. Off-board countermeasures also can be used by an aircraft for self-protection. Examples are chaff, towed or active expendable jammers to capture the guidance of RF homing missiles, and flares, which have been popular for capturing the guidance of heat-seeking missiles. High levels of immunity to chaff have been obtained by the use of leading edge track in the radars, Doppler processing in both radars and missiles, enhanced range resolution features, and other moving target indicators. The target can be resolved from the towed and expendable jammers by complementary sensors that operate at significantly different wavelengths (i.e., multispectral systems). The very narrow beam widths associated with short-wavelength sensors, such as IR, can provide the angular resolution required to resolve the target from decoys near it. **A.** Chaff. **B.** Expendable decoy. **C.** Towed decoy.

lution and target motion, the fleet could win most conceivable encounters with chaff.

Decoys using small jammers could create different and more challenging problems than chaff, however, for both the shipboard systems and the missiles. The jammers in these devices might generate noise and apparent false target signals with various velocity and range profiles. These could make discrimination between the desired target and the decoys difficult.

In the early 1960s, APL recognized that a radar or a missile probably could not win future contests with such off-board countermeasures by relying solely on one sensor. Accordingly, the Laboratory believed that radar and missile homing guidance ultimately had to involve the fusion and/or correlation of data obtained from different sensors operating in different parts of the RF, electro-optical, and IR spectra. Efforts directed toward the collection, fusion, and automatic processing of data obtained from diverse sources continue to this day.

Figure 8 shows a multispectral missile conceived by APL's Joseph F. Gulick[3] in the early 1970s. Homing guidance in this AAW missile is provided by both an RF interferometer and an IR sensor.

The Laboratory also is pursuing a distinctive signal processing concept, based on work done by the late James E. Hanson, that permits an RF homing missile to establish independent track files on closely spaced multiple sources coexisting in the main beam of the missile's antenna (e.g., a target deploying self-protection decoys; Fig. 9). The technique has special value if the jammer can prevent the missile from resolving the two sources by measuring the differences in range and/or Doppler; that is, the missile is forced to resolve in angle only.

Support Countermeasures

A classic example of a support countermeasure is standoff jamming, in which jammers are placed at distances typically beyond the range of air defense missiles and radiate high levels of noise jamming to protect ingressing attack aircraft and missiles. Simply stated, this type of support countermeasure is a power contest between the opposing players. The jammers must radiate sufficient power to conceal the defended aircraft and missiles from the air defense systems, and the air defense systems, in turn, must be configured so that the radars and missiles can detect and engage their targets, despite the jamming.

Missile performance in this environment is enhanced by the use of midcourse guidance, followed by relatively

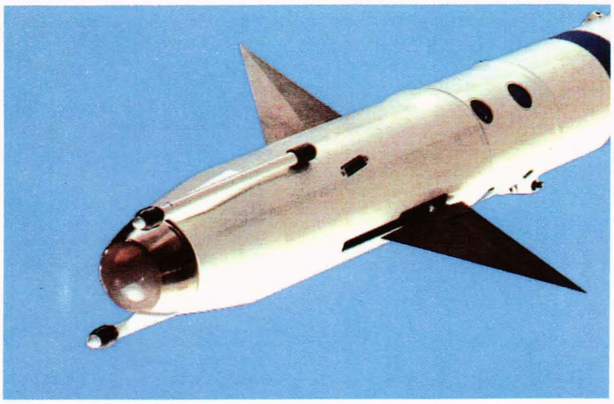

Figure 8. Numerous configurations of a multispectral missile homing system have been considered by both APL and industry since the 1960s. An example of a dual-spectral missile is the Rolling Airframe Missile, which uses RF guidance for the initial homing phase with transition to a highly accurate IR system for the final seconds of flight.

short homing. The outcome of the contest between the missile and the stand-off jammers increasingly favors the missile as it gets closer to the target. The homing phase is only long enough to remove the midcourse guidance and target queuing errors.

Early modifications to both surveillance and fire control radars to improve the fleet's positions in this contest included truly random frequency agility, which forces the jammer to spread its power over a wide band. This, in turn, dilutes the jammer power in the radar receiver. An APL-designed digital intrapulse phase-modulated, pulse-compression feature also was added to some of the fire control radars. Pulse compression allows the radar to take advantage of the relatively high average transmitter power and coherent pulse-Doppler processing possible with a long (high-duty factor) transmitter pulse, while obtaining the excellent range resolution possible with a very short-pulse waveform. The random phase-coded modulation provides a high level of immunity to ECM. Numerous other ECCM features were developed, such as one that automatically determines whether the jamming is for self-protection or from a stand-off jammer.

Finally, the automatic fusion and correlation of target data from multiple sensors discussed earlier are major elements in countering support countermeasures. Especially significant are the target data collected and shared between various ships, aircraft, satellites, and so on. With good fusion of these data, it will be difficult for stand-off jammers to effectively hide the ingressing threats from all sensors on all the fleet's platforms (Fig. 10). Simply, an entire battle group literally becomes a massive integrated weapon system.

CONCLUSION

The adversarial threat philosophy that has underlined APL's approach to countermeasures since the 1960s has been beneficial to those in the Navy involved with electronic warfare. By going beyond the known threats at a given time, and by considering what an informed adversary might do in the future, the Navy's surface fleet has been put in a good position in the countermeasures game. The implementation of fundamentally sound ECCM designs in the radars and AAW missiles and the ongoing efforts to correlate and fuse threat data obtained from diverse sensors (not only on a given ship, but throughout a battle group) have made today's fleet a formidable opponent to any potential adversary.

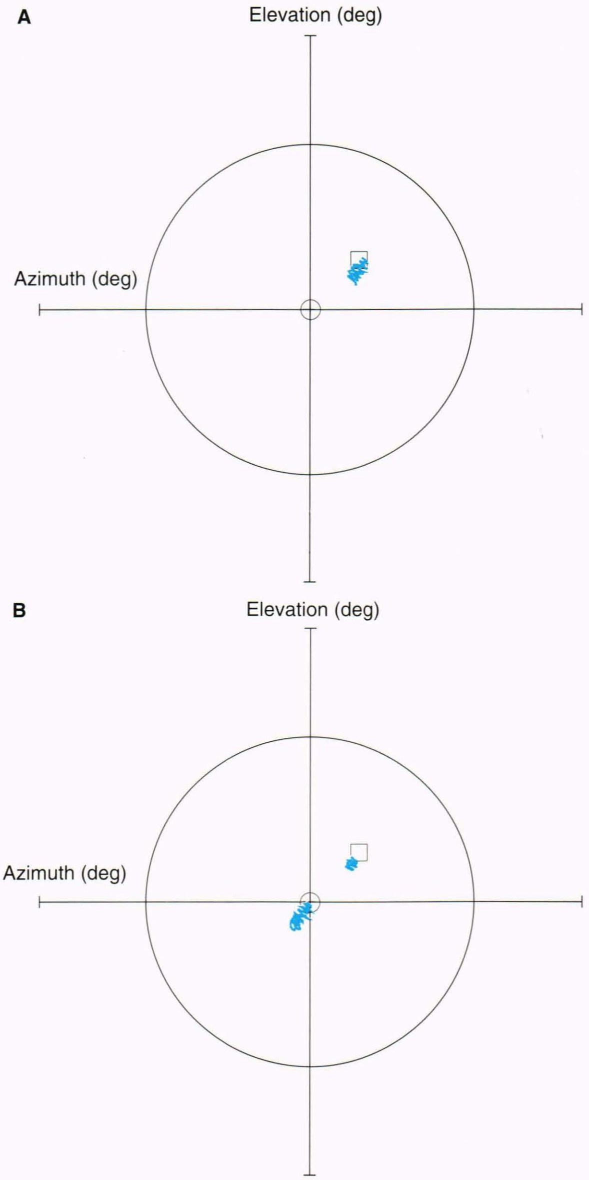

Figure 9. New monopulse angle measurement techniques make it possible to resolve multiple, closely spaced RF sources that coexist in the main beam of a monopulse radar or missile seeker. Illustrated are results of anechoic chamber angle tracking tests involving two remote RF sources. One source is a noise jammer (square), whereas the other is a target echo (circle)—a situation similar to a towed or an active expendable jammer deployed by an attacking aircraft for self-protection. The amplitude of the jammer signal was greater than that of the target signal. **A.** For conventional signal processing, this resulted in a single track on the jammer. **B.** For the modified system, using an algorithm developed by James Hanson, tracks were established on both sources.

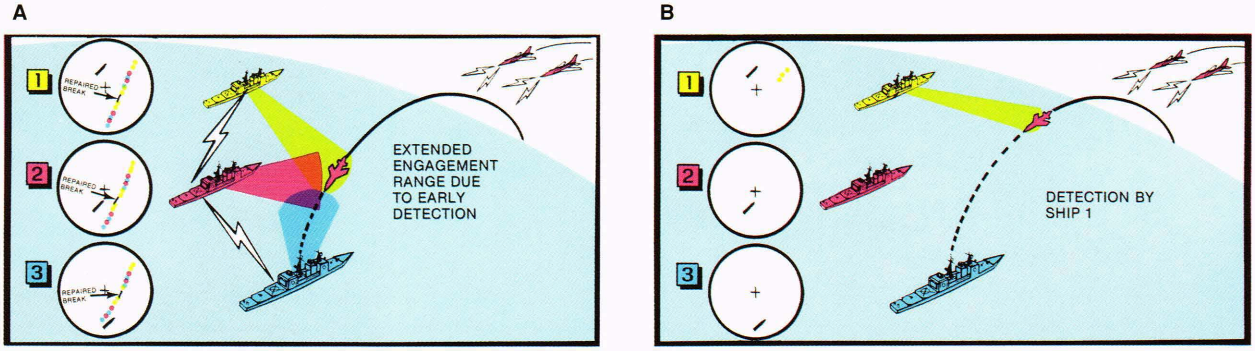

Figure 10. A simple example of how data sharing between various elements of a battle group provides all ships an enhanced picture of the threats. **A.** An anti-ship missile targeted on ship number 3 cannot be detected by ship 2 or 3 because of the stand-off jammers and/or the radar horizon. Ship number 1 establishes the first track, which is then reported to ships 2 and 3. This track information is then used by ships 2 and 3 as a search cue. **B.** All three ships eventually establish independent tracks. As these track data become available, they are assembled into a composite track picture, which is identical on all three ships. The composite track picture overcomes the support jamming, multipath, and radar horizon limitations otherwise associated with individual ships.

The contest is not finished, however. Potential threats and ongoing programs to counter them still exist, and the work must continue. As we look to the future, evolving technology will enable potential adversaries to develop or purchase increasingly sophisticated equipment. Future jamming systems will be smaller and fully automatic. They can be installed on virtually any platform (e.g., unmanned aerial vehicles, anti-ship missiles, and so on) and will be able to simultaneously confuse multiple systems. To compete with these future threats, the Navy must continue to address them today; the cost will not be trivial, but the consequences of ignoring them are totally unacceptable.

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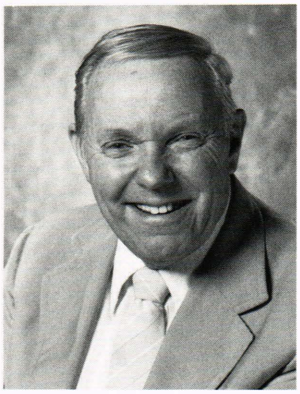
THE AUTHOR



W. COLEMAN HYATT attended The University of Maryland. He joined APL in 1956 and is currently a member of the Principal Professional Staff in the Naval Warfare Analysis Department. Mr. Hyatt was active in the design, testing, and evaluation of Talos guidance and has served on numerous government teams assembled to address system development requirements, contractor source selections, and performance assessments of many air defense missiles. Mr. Hyatt is a member of the Association of Old Crows (AOC) and has contributed to the development and teaching of an AOC short course on the fundamental principles of electronic warfare, which has been presented by APL to DoD, military, and industrial personnel throughout the country.