Military

Radar: shield or target?

Costly radar being developed by the U.S. may give an opponent a decisive advantage by broadcasting the position and makeup of forces

It is fashionable in some military circles to belittle infantrymen as deficient for not availing themselves of all the latest technology. But this much is sure: no sane infantryman engaged in heavy combat would run to the top of a nearby hill, light a flare, and dare the enemy to hit him. Yet some $50 billion a year of the United States defense budget goes to develop, buy, and support radar systems that do the electronic equivalent of exactly that. For 20 years, many in the U.S. defense establishment have been aware of this problem but have swept it under the rug.

Simply put, the radar-dependent systems being developed and deployed by the U.S. give an opponent a decisive advantage by broadcasting the position and makeup of military forces to anyone who chooses to tune in. They are excellent aiming points for anyone who wants to shoot at U.S. missiles, planes, warships, and ground units. All an enemy need do is deploy low-cost antiradiation missiles capable of homing in on the radiating antennas of the U.S. radar *long before the radar can detect the presence of the enemy.* The range of U.S. radar is limited to line of sight; an inexpensive radar seeker, using passive sensors that do not radiate any energy, can detect fire at a radar system from over the horizon.

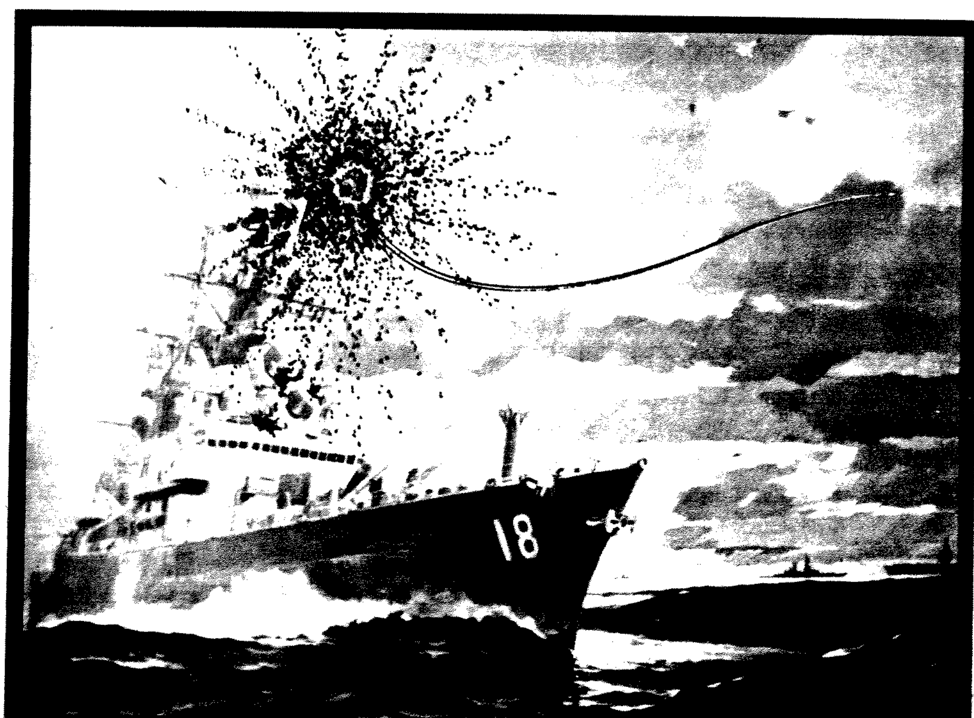
This vulnerability of U.S. equipment was amply demonstrated in the Vietnam War when U.S. missiles, designed to home in on enemy radars, did indeed work—but not always as intended. U.S. Shrike missiles hit U.S. Marine units that had not shut down their radars. Similarly a Shrike accidentally attacked the U.S. destroyer Worden in the Gulf of Tonkin; it homed in on the ship's radar, exploded 100 feet directly over the superstructure, and disabled the ship's command center [Fig. 1].

Thomas S. Amlie

Past lessons ignored

Such warnings appear to have done no good. The U.S. proposes, for example, to build B-1 bombers designed to fly deep into enemy territory while depending for navigation on terrain-following radar. Such continuously radiating radar signals can be easily detected by an enemy.

The solution is not to eliminate radar, but rather to design new radar systems. To reduce their vulnerability as targets, such radars could be used in brief bursts sufficient to find the range of targets, while passive nonradiating sensors are used for angle tracking. Since radar-seeking missiles must have antennas that are at least one-half wavelength in diameter—and preferably 3 to 4 wavelengths—the high-frequency stationary radars that the U.S. has been using for so many years could be replaced in some applications with low-frequency systems in the range of 100 to 400 megahertz. The low-frequency systems would be invulnerable to radar-seeking missiles because the missiles could not carry the necessary large antennas. Moreover these new



[1] The U.S.S. Worden, shown in this artist's rendering, was accidentally attacked by Shrike missiles that homed in on the ship's radars as it steamed in the Gulf of Tonkin during the Vietnam War. The incident illustrates the vulnerability of radar-based weapon systems to antiradiation missiles that can home in on radar antennas through the use of passive sensors.

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radars might be so sensitive that they could detect even a "stealth" aircraft.

A 100-MHz radar, the conventional wisdom holds, is easily jammed, and it also interferes with commercial television signals. However, the fact is that the North Vietnamese used such radars with impunity in the Vietnam War; U.S. forces could not hit them, and they seemed to locate U.S. aircraft efficiently.

The guiding principle insofar as military radar is concerned is this: If U.S. radar is silent, the enemy must radiate to find U.S. targets and thus becomes more vulnerable. Properly used, radar can give U.S. military forces a decisive advantage by locating enemy missiles, aircraft, warships, and battlefield weapons without giving away the radar's position.

U.S. radar now easily detected

The present U.S. military radars radiate strong and distinctive signals. The North Atlantic Treaty Organization (NATO) and the Warsaw Pact nations alike have deployed well-equipped electronic intelligence (Elint) ships and aircraft around the world to listen for and catalogue each other's transmissions. Inasmuch as the radiation of most radar systems can be received clearly (there is a high signal-to-noise ratio) at long distances, one must assume that all major systems that are deployed have already been catalogued.

Ships or aircraft that operate in a formation must, so long as their radars operate full time, have the radars tuned to different frequencies to avoid interfering with one another. Thus a listener with simple receiving and signal-analysis equipment, plus catalogue information, can know where the formation is, how many ships and aircraft there are in it, and what types they are. An argument can be made that the U.S. has gone to great trouble and expense to offer an enemy information that can be used against it.

It is worth looking at the following major U.S. weapon systems: the Patriot battlefield air-defense systems, the F-14 and F-15 tactical aircraft, the Aegis class of missile-carrying cruisers, and all-weather bombers with supposedly accurate radar-directed bombing.

Although $4 billion has been spent so far to develop the Patriot system (when deployed, each firing unit will cost at least $80 million), it will be one of the few targets that enemies will be able to hit in bad weather, simply because it radiates powerful radar signals. By the same token, the F-14 and F-15 are designed around expensive and troublesome radar-controlled weapon systems that have rendered the aircraft not only relatively unreliable but also easily attackable by radar-seeking enemy missiles.

Meanwhile the Navy contends that the radar-controlled missiles on the CG-47 Aegis-class cruiser—a ship that is actually a modified destroyer (the DD-963)—will be an umbrella of defense for carrier task forces. The advanced radars on the new ship have raised the cost of each destroyer to $1.4 billion—compared with $400 million for the destroyer versions—yet the big question still is: What will protect the Aegis system itself?

Ships are already excellent radar targets because of their huge radar cross sections, but their radar transmissions are even more important to an enemy. These signals can be detected over the horizon, because the open sea poses almost no problem with clutter (radar reflections from the land or sea surrounding a target), whereas the density gradient of water vapor at the sea surface may allow radar waves to follow the earth's curvature.

The U.S. Air Force is also mistaken in its plan to upgrade current radar-bombing systems through image enhancing based on Doppler beam-sharpening techniques. Although the U.S. has spent billions of dollars since the middle of World War II to develop radar systems to bomb accurately at night and in any weather, the "circular error probable" in the Vietnam War was still as much as about 1.2 kilometers (0.75 mile)—utterly useless with conventional high explosive bombs with a lethal radius of about 4.5 to 9 meters (15 to 30 feet). (The circular error probable means the radius of a circle within which at least half the bombs fall; the hope is that the center of the circle will be near the target.) Even if the performance were improved by a factor of 10, the system would still be useless. Air crews are ill-advised to fly deep into enemy territory in planes that radiate strong radar signals from a weapon system that will probably not damage the

The Navy replies: solution is too simplistic

In his overwhelmingly inclusive paper, Thomas S. Amlie proposes a simple panacea for all problems of offensive and defense missilery—be they Army, Air Force, or Navy. He suggests that antiradiation-missile (ARM) technology is the universal solvent capable of dissolving the technical, management, tactical, and strategic weaknesses of our anti-aircraft-warfare (AAW) and strike programs.

While I cannot agree with the simplicity of Mr. Amlie's approach, or with most of his hypotheses and conclusions, I can agree that we should continue to develop and exploit the promise of ARM and electrooptics technology.

From the Naval viewpoint, there are three main areas in which I believe Mr. Amlie's analyses to be incomplete. Firstly, there is inadequate emphasis on the *system* aspects of AAW. An effective AAW system must include detection, tracking, classification, targeting, command and control, missile-in-flight support, and engagement. The system capability is really only as good as the weakest of these links.

Secondly, there are basic differences in our understanding of the Navy's roles and missions. A Navy battle group's mobility permits it to exercise sea control throughout the ocean areas of the world. By definition this requires the capability to impose air superiority on a temporary or permanent basis. This mobility exposes a battle group to the spectrum of enemy threats from land, air, surface, and subsurface threats that are presented in a wide variety of tactical scenarios. Nonradiation could be effective in support of clandestine ocean transits but perhaps catastrophic in Gulf of Tonkin, Mediterranean, or Indian Ocean scenarios.

Thirdly, I am not as sanguine as Mr. Amlie about the universal efficacy of ARM technology. The differences between engaging a fixed radar site or a slow-moving ship and a supersonic missile target are nontrivial. Also, Mr. Amlie talks of an "ARM receiver of the superheterodyne type" with a tunable local oscillator that could lock onto one target radar of many in a wide frequency band. Modern radars are agile on a pulse-by-pulse basis over a wide bandwidth. The superheterodyne receiver and tunable local oscillator scheme would be ineffective in this situation.

In summary, ARM technology in the hands of an enemy is of very real concern—one which the services have recognized and worked to exploit and counter for two decades. It also offers a useful approach (among others) to our weapons. The subject must be addressed in the perspective of all combat techniques. If Mr. Amlie had a specific technical suggestion that might add to the assessment, it could contribute to progress. He has not offered one. —*Wayne E. Meyer*

For over a decade, Rear Admiral Wayne E. Meyer has directed the development of the U.S. Navy's Aegis warships.

intended targets.

At the same time some U.S. radar-guided missile systems send a clear signal to the target that a missile launch is imminent by turning on an illuminator that locks the search radar in angle-tracking mode, changing the transmitter format and so on. An aircraft target warned by this information can maneuver abruptly or initiate other countermeasures to defeat the missile.

Most of the current U.S. radar-guided missiles are either active or semiactive. An active missile carries its own transmitter and is essentially a small and very expensive radar. A semiactive missile has no radar of its own; it depends on the launch vehicle to illuminate the target and then homes in on the energy reflected by the target. But the energy reflected by the target is generally quite small and allows only modest lock-on ranges. In many situations the energy reflected by the water or terrain near the target is much more intense than the target signal, so that range- and Doppler-filtering and pulse-compression techniques may be required for useful performance. These, of course, add to the missile's cost and complexity.

Missiles can home in on radars

On the other hand, a passive-homing antiradiation missile (ARM), designed expressly to home in on radars, has essentially none of the problems of the active and semiactive missiles. The signal-to-noise ratio is, for practical purposes, infinite; the victim radar is a point target; the ground or sea clutter problem is greatly reduced and there are usually no interfering signals.

The passive ARM can also solve another very difficult problem: that of target identification. The armed services have spent many years developing antiaircraft missiles with very long firing ranges; they are called "beyond visual range" (BVR) missiles, and very substantial resources are spent every year to develop, acquire, and support them. However, U.S. forces cannot fire in wartime at every blip that appears on the radar screen; it might be one of their own or that of a neutral country. Thus the military is forced to identify visually before firing, and the BVR missile becomes in practice "within visual range."

Positive visual identification of other aircraft is possible only at about 4 to 8 km under good conditions. The passive ARM solves this vexing, and to date intractable, problem with a microprocessor and a catalogue of military signals by classifying a received signal as friendly, hostile, or "don't know." The seeker range of the ARM is very long, and the firing range is limited only by the missile propulsion one is willing to pay for and carry. The ARM can be fired in the sidelobes or backlobes of the target radar antenna, so an attacker can fire without announcing his presence. The ARM seeker, working with strong point targets and minimal interfering signals, should be simpler, cheaper to build, and more reliable than an active or semiactive missile seeker.

The advantages of firing unnoticed

Since the signals an ARM homes in on are strong, it can be fired at long ranges—for example, from a surface vessel at a radiating ship well beyond the horizon. The crew of the target ship would be unaware of the attacker's presence or that a missile was on the way. An ARM can be designed to have, head-on, a very low radar cross section that is difficult to detect. This is especially true if it is flying very low over the water and the radar must detect it in the presence of heavy sea clutter.

An argument sometimes advanced is that the ARM will become confused when attacking a formation of platforms carrying several radars in the same frequency band. Early ARMs did have this problem, because they used very wideband receivers. The ARM discussed here would have a superheterodyne receiver with a radio-frequency bandwidth approximately matched to that of the target to be detected and attacked, as well as a tunable local oscillator covering the frequency band of interest, so one target could be selected from among many. Most currently deployed radars require tuning to a frequency different from that of nearby radars to avoid interference. The ARM designer can also use "angle gating" so that the seeker rejects signals that are more than a degree or so off antenna bore sight.

It may be argued that radar designers could use techniques such as frequency diversity, pulse compression, and other spread-spectrum approaches to defeat the ARM. However, these techniques increase the cost and complexity of the radar and would take a long time to implement. It is also argued that if such systems were deployed, a potential enemy could gather electronic intelligence catalogues on them in peacetime and change the signal processing in the ARM. But though this would make the task of the ARM more difficult, the angle-gating technique would still allow it to function properly.

Fighter aircraft are targets

The present tactic with U.S. fighter aircraft is to search for enemy aircraft with airborne interception (AI) radar and to shoot radar-guided missiles at them. This concept has two problems:

1. AI radars that operate continually could attract highly lethal ARMs. The radars aboard all modern U.S. fighter aircraft (F-14, -15, -16, and -18) are sufficiently close in frequency so that one model of an air-to-air or surface-to-air ARM could be used against all. If an adversary deployed such ARMs, our pilots would either have to turn off their radars or suffer losses.
2. Radar-guided air-to-air missiles are expensive (up to $2 million each) and not particularly reliable, having demonstrated a probability of kill per shot of approximately 10 percent in the Vietnam War. (Soviet SAMs scored less than 1 percent of the time.) It is claimed that follow-on versions of the missile will do better, but this has yet to be demonstrated.

The argument that these super-powered airborne radars and long-range air-to-air missiles are necessary should be reexamined in light of the fact that ARMs can be fired outside of active radar range, no matter what the range is. The ARM must obviously have the necessary propulsion and aerodynamic range.

The U.S. Navy has an especially difficult problem. The damage done by Japanese kamikazes at Leyte Gulf, Iwo Jima, and Okinawa during World War II was a foretaste of the age of antiship missiles. The kamikazes were generally slow and obsolescent aircraft flown by poorly trained pilots, and most were shot down before they did any damage. Those that did get through sank or severely damaged over 300 ships and inflicted some 15 000 casualties by the end of the war. This lesson, while largely ignored by the U.S., was not lost on the Soviet Union. It has long since deployed various versions of air-launched and surface-launched antiship missiles in large numbers. These missiles, which attack at speeds of 500 to 600 knots, are small and difficult to detect and even more difficult to shoot down.

If turning on radar gives an enemy more advantage than it gives the U.S., the important questions are:

- What sort of weapon systems can the U.S. design that do not have to radiate full time?
- Will a force equipped with these systems prevail against a radar-equipped adversary?

These questions can be answered by examining current air-to-air, air-to-ground, and battlefield weapon systems.

U.S. fighters are large and expensive mainly because of their large and costly radar fire-control systems. If pilots have to turn these systems off in combat because of air-to-air ARMs, the U.S. might be better off buying many more simpler, higher-performance, smaller machines at a much lower unit cost.

The YF-16 delivered to the U.S. Air Force in 1974 was the finest high-performance fighter in the world. However, the Air Force technical bureaucracy promptly added expensive equipment—most of it irrelevant to combat requirements—that raised the acquisition and maintenance costs. It also increased the fighter's weight by about 4000 pounds and thus reduced maneuvering and accelerating performance. If this extraneous equipment were replaced by better radar homing and warning receivers, by air-to-air ARMs, and by the latest version of the infrared-homing Sidewinder air-to-air missile, the resulting aircraft would perform superbly. It would still require a capable AI radar to determine if the radiating targets the ARM seeker detected and classified as hostile were within aerodynamic range, because the ARM seeker range is much longer than the aerodynamic range in almost all cases. But the radar would be operated only in short bursts to determine target range. The F-16 has an excellent AI radar that, with modifications, would do well for this purpose.

How would a force armed with this aircraft do against a force armed with large aircraft and weapon systems predicated on the full-time use of radar? The smaller aircraft would be harder to see, and if the pilots of the big aircraft turned on their radars, the pilots of the smaller planes would know where and how many they were and could attack from long range undetected. If the pilots of the larger aircraft chose to keep their radars off and to engage at close quarters, they would be at a further disadvantage, since their aircraft would be easy to see and less maneuverable than the smaller aircraft.

Most important, the U.S. could have three to four times as many of the smaller machines in the air than it would if it had spent the same resources on large aircraft that required the full-time use of radar. The aircraft unit price would drop by a factor of three or so. Much less maintenance would be required, technicians could have less skill, and the plane's availability would be higher than the 25 to 55 percent currently experienced in peacetime (wartime availability would be less). Superior numbers are important in war; the current emphasis on quality over quantity may be counterproductive.

Air-to-ground hits without radar

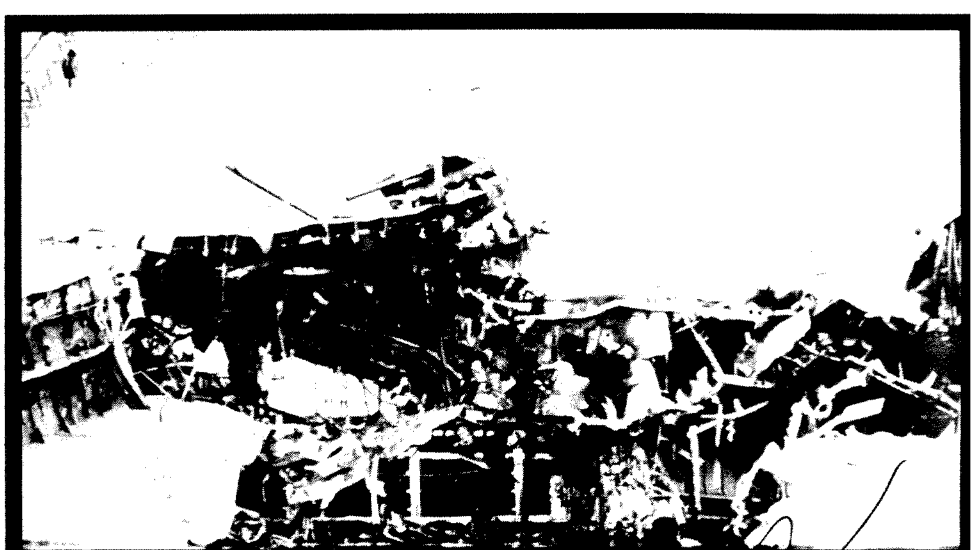
Similar arguments can be made with regard to attack aircraft, particularly radar-bombing planes. Even if radar-bombing accuracy could be improved sufficiently to give useful results, and even if surface-to-air and air-to-air ARMs were not a potential problem, radar bombing would be useful only against large, prominent, fixed targets, such as factories, power plants, large buildings, and the like. It is difficult to justify the urgency of hitting these targets on a particular night or day in bad weather. Presumably they will still be there when the sun comes up or the weather clears.

If there is a requirement to hit prominent targets in well-defended areas deep in enemy territory, television-guided standoff missiles, particularly those with a video data link to the pilot operator and a command link back to the missile, have demonstrated the capability to reliably put a l-ton warhead within a few feet of any desired point on a large and visible target. The standoff range is limited only by how much missile propulsion and data-link capability one is willing to pay for and carry.

The fleet is in trouble

The Navy has an almost insoluble problem, because ships are excellent radar targets and ships' radars are even better targets. Operationally the task-force commander has three basic options: (1) operate the radars full time; (2) operate the radars part time, possibly with ships taking turns searching and sharing their data; and (3) maintain radio and radar silence. Option 1 makes the task force vulnerable to detection, identification, and surprise attack by ARMs. Option 3 would eliminate the vulnerability to ARMs and, with suitable radar homing and warning equipment, would allow active and semiactive antiship missiles to detect the attack. However, it would leave the task force vulnerable to attack by missiles with infrared terminal homing. Submarines with passive sonar arrays can detect surface ships at great distances, so that a task force can be found but not necessarily identified. Common sense and the results of fleet exercises dating to the 1960s strongly indicate some mixture of options 2 and 3 as the U.S. Navy's best choice.

One surveillance technique that has not been given enough attention is that of passive infrared. Most antiship missiles use rocket motors or turbine engines for propulsion. Modern IR search sets are very sensitive and have good background discrimination. The argument is made that if the weather is good enough for the missile to find the ship, it is also good enough for the ship to detect the missile. What to do about the detected enemy missile is, like the case of the radar-guided antiship missile, another very difficult problem. The solution might in-



[2] This U.S. Naval vessel suffered extensive hull damage during a training exercise when an attacking missile, although hit by defensive missiles launched from the ship, continued on its ballistic path and struck its target.

Theory versus practice

Though textbooks expound the solidly proved principles of radar engineering, differences may exist between textbook concepts and actual practice in the field. Indeed, the following alleged gaps between theory and practice in two areas underlie the disagreement between Mr. Amlie and the "radar establishment" (as represented in today's radar-dependent U.S. weapon systems):

1. According to the textbooks, a radar system can defeat passive antiradiation missiles (ARMs) through frequency hopping—programmed changes in the transmitter frequency that make it statistically impossible for sensors on the ARM to home in on the transmitter. Mr. Amlie contends, however, that the equipment needed for frequency hopping is too expensive and has not been deployed.

2. ARMs can also be defeated, in theory, by shutting down the transmitter entirely, or achieving equivalent results by transmitting into a dummy load. But Mr. Amlie says these measures are impractical in the field, since lengthy procedures are needed to turn the systems on again; meanwhile, he points out, U.S. radars have such powerful signals that they leak detectable radiation even when transmitting into dummy load.

Textbook theories do, in fact, indicate that frequency-hopping radars would be difficult to home in on with the relatively simple equipment that Mr. Amlie envisions on passive ARMs. An expert in military radar supplied *Spectrum* with an example that illustrates how impractical it would be to make an intercepting receiver with matched filters.

"Assume," he said, "an X-band [gigahertz] radar using coherent bursts of 1-microsecond pulses with repetition rates of 1000 to 2000 pulses per second during a 20-millisecond dwelling time. There are about 1000 possible radio-frequency channels in the 1-GHz tuning band; in each RF channel, for each resolvable repetition rate, there are 20 000 possible delay-frequency cells in which contiguous matched filters can be placed by calculating the fast Fourier transform of the signal. This gives 20 million detection filter cells at a specific pulse-repetition rate; since there are about 10 thousand resolvable repetition rates, a total of 200 billion possible matched filters would have to be implemented in the intercepting receiver carried by the ARM.

"Obviously, the intercepting receiver must make gross approximations in RF bandwidth, time-gate width, and Fourier-transform filter bandwidth to reduce the complexity factor perhaps by a factor of 10 thousand. Even so, 20 million matched filters would have to be tested every 20 ms for a possible signal with some 30 decibels less signal-to-noise ratio than is available in a matched filter."

A wise designer of intercepting receivers might not, therefore, depend on matched filters to home in on a frequency-hopping radar target. However, several sources report that frequency hopping is not used in such major U.S. weapons systems as fighter planes, AWAC (Airborne Warning and Control) planes, and other standoff target-acquisition systems. One may assume, Mr. Amlie contends, that Soviet electronic-intelligence ships and planes have already catalogued the radar-transmission characteristics of these weapons systems. If that is the case, he says, a matched filter intercepting receiver would be inexpensive to implement as well as reliable.

But according to one of the nation's most senior radar engineers, the receiver's reliability is questionable. Its uppermost problem, he notes, is that it would be incapable of resolving the desired sidelobe signal, which varies over tens of decibels, in the presence of dozens or hundreds of similar detectable signals. *—Robert Bernhard*

volve use of decoys to confuse the incoming missile, IR-guided defensive missiles, radar-guided defensive missiles, or radar-directed guns.

The use of off-ship decoys (both IR and microwave emitters), corner reflectors, and transponders on towed sleds or other small vessels would greatly complicate an attacker's problem and could help in defeating ARMs as well as IR-guided and radar-guided missiles.

A major part of the U.S. Navy's plan to meet the air-to-surface missile threat involves sending the F-14, armed with the long-range Phoenix missile, to intercept the aircraft (typically the Soviet Backfire bomber) carrying the antiship missile. It can be postulated that some Soviet design bureau has come up with a seeker to home in on the F-14 radar and has installed it in a few Soviet AS-1, -2, -3, -4, -5, or -6 missiles or in AA-6s. Such a seeker would be easy to build and would fit nicely in a 2-pound coffee can. This would transform the F-14 from the hunter into the hunted. With modest jamming by the Backfire, the F-14 crew would not know that a missile had been launched and particularly would not be aware that it was homing in on them.

The Navy might consider one more move in this deadly game and modify the seekers in a few of its own *standard* ARMs so they would lock better onto the Backfire radar in preference to all other targets. This would completely reverse the situation. The F-14 would transmit only occasional short bursts of radar for ranging, and the Backfire would be compelled to use its radar to attack if the U.S. task force was not radiating.

The Navy might also profit by studying the advantages of lower-frequency search radars. Excellent performance can be achieved at lower cost in the VHF and UHF bands, and these radars would be difficult to hit with ARMs. With Elint information on Soviet combatants, ARM seekers in at least a few U.S. cruise missiles would give the Russians pause about operating the many radars they typically put on a ship.

To probe further

The bibles of radar engineering are *The Radar Handbook*, edited by Merrill I. Skolnik, McGraw-Hill Inc., New York, 1970; *Introduction to Radar*, also by Mr. Skolnik, McGraw-Hill, 1962; and *Radar System Analysis*, by David K. Barton, Prentice-Hall Inc., Englewood Cliffs, N.J. 1964. An elementary and readable discussion of radar is found in *Modern Radar: Theory and Operation*, by Edward L. Safford (Tab Books Inc., Blue Ridge Summit, Pa. 1981).

No books or articles have been available so far that focus on the vulnerability of radar systems to passive antiradiation missiles. However *Defense Electronics* (November 1981, p. 7) does touch on this issue in an editorial titled, "Turn it off, turn it off," by editorial director Richard Hartman. The threats posed by ARMs that home in on radar signals, Mr. Hartman writes, "may force the navy back into the old practice of steaming in electronic silence."

About the author

Thomas S. Amlie received a Ph.D. degree in electrical engineering from the University of Pennsylvania in 1952. He was technical director of the Naval Weapons Center, China Lake, Calif., from 1968 to 1970. From 1970 until his retirement in 1980, he worked for the Federal Aviation Agency on research-and-development programs for collision-avoidance systems, radar, and microwave landing systems. Early in his career he ran the Sidewinder-missile flight-test program for the U.S. Navy (1957) and was in charge of designing a radar-guided version of the same missile (1957 to 1964). ◆