History of Key Technologies

Development of Low-Altitude Air Defense Systems

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Introduction

CONVENTIONAL pulse radars cannot detect low-flying aircraft because the power reflected from the ground masks the smaller power reflected from the aircraft. Recognition of this fact as far back as World War II provided the impetus to develop "Doppler" radars, which separate the target and ground clutter signals by using the Doppler frequency difference generated by the velocity of the aircraft relative to the ground. The first Doppler radars were continuous-wave (CW) radars, pioneered by Raytheon Co. in the Sparrow and Hawk missile systems (and subsequently adopted by the U.S. Navy and the U.S.S.R.). The fundamentals of these techniques were later applied by a variety of contractors to pulse-Doppler radars, which combine some of the characteristics of pulse and CW radars.

The present paper provides a historical review of key events in the Raytheon CW radar development, with primary concentration on the early 1950's, the period of most rapid progress. The paper is intended to complement the author's paper entitled "The Development of Radar Homing Missiles," published in this Journal in 1984. In the present paper I have amplified a particular aspect of the air defense problem that is discussed only in general terms in the reference. The reader is referred to the reference for additional background information that provides a more complete understanding of the period covered in this paper, and more detailed discussion of the problems overcome in other missile-design areas.

Although this paper is not intended as a technical treatise, it is not possible to review the significant events without discussing the nature of the technical problems and the general approach followed in solving them. I have attempted to do so in a manner that will be understandable to the nonspecialist—i.e., by relating them to well known physical principles and without resorting to mathematics.

Background

Conventional pulse radars operate by transmitting high-power pulses of very short duration (typically of the order of a microsecond, or 1 μs), and examining the reflected energy in time intervals of the same length. When there are no interfering signals present, a target return can be detected (either manually or automatically) when it exceeds receiver noise by a sufficient amount, typically 12 dB (4 times in voltage or 16 times in power). Although the returns from multiple pulses can be added, the random nature of the radio frequency (rf) phase from pulse to pulse prevents the addition from being done coherently, i.e., prior to detection. Instead, only postdetection integration is possible.

When the target is flying at a sufficiently low altitude that the radar main beam intercepts the ground, the large illuminated ground results in a reflected power (called "clutter") that is typically several orders of magnitude larger than the power reflected from the aircraft, and aircraft detection is thus denied. Multiple-pulse returns are added equally for clutter and target signal, and so no advantage is gained by integration.

The clutter problem was recognized early in radar development history and led to a decision by Royden Sanders to pursue a different type of radar, one that utilized the Doppler frequency of a moving target as its basic signal, which then could readily (in principle) be separated from stationary non Doppler shifted ground clutter. Sanders eventually found a sympathetic ear in Laurence Marshall, president of Raytheon, who set up a laboratory to pursue the ideas. A contract was obtained from the U.S. Navy in 1944 to develop a Doppler radar for guiding a Lark missile to provide defense against the very serious Kamikaze aircraft attacks against Allied ships in the Pacific theatre.

Sanders concept for this radar was a simple one: a continuous-wave radar defined as one that transmits a continuous, fixed-frequency signal—a single tone when viewed in the frequency domain. A narrow frequency filter, called a speed gate, would be used to coherently integrate a long period of signal returns (typically 1000 μs) to provide frequency discrimination of 1 kHz (50 ft/s at 10 GHz radar frequency), and thus separate the aircraft signal from the ground clutter (Fig. 1). The speed gate would search the relevant frequency spec-

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EDITOR'S NOTE: This manuscript was invited as a History of Key Technologies paper. It is not meant to be a comprehensive study of the field. It represents solely the author's own recollection of events at the time and is based upon his own experiences.

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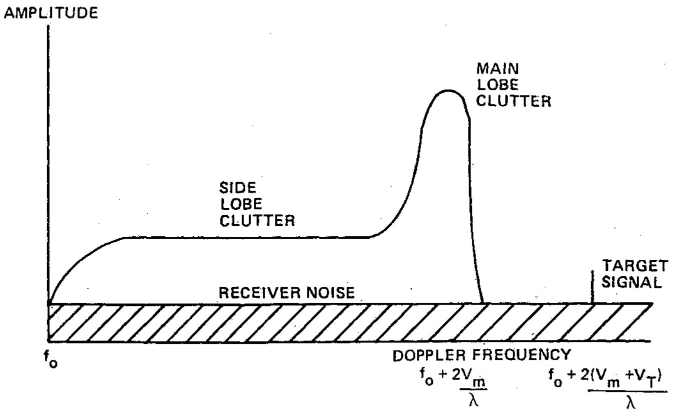

Fig. 1 Doppler radar spectrum from moving missile.

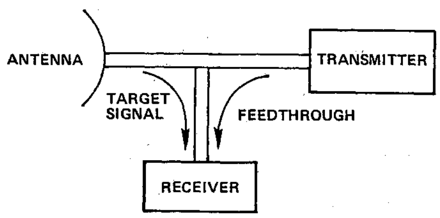

Fig. 2 Feedthrough problem in CW radars.

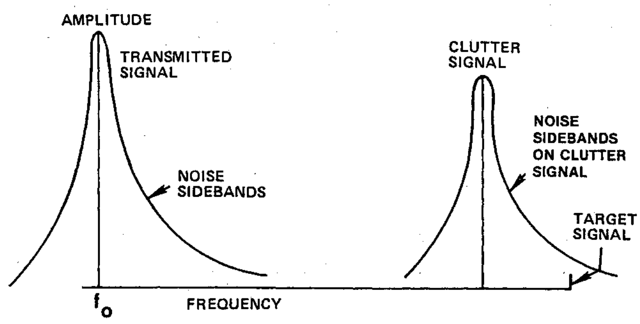

Fig. 3 Noise sidebands in Doppler radar.

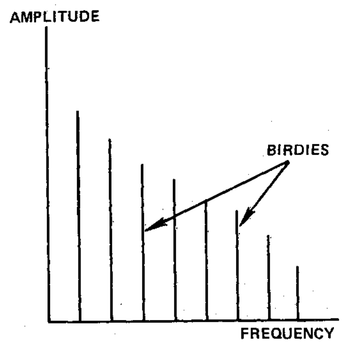

Fig. 4 "Birdies" in Doppler radar.

trum for a pure tone at an offset frequency representing the signal from a moving target, stop searching when a target was detected, and then track that signal, providing guidance commands to the missile.

Fundamental Technical Problems

There were some serious technical problems with the guidance system. Some were fundamental to target detection in a cluttered environment; others were more prosaic engineering problems in applying the technology of the day to equipment that was capable of operating in the severe missile environment. The fundamental problems are characterized below as "feedthrough," "noise," and "birdies."

Feedthrough is a problem unique to CW radars (Fig. 2). Pulse radars very sensibly turn their receivers off when their transmitters are on. CW radars transmit continuously and thus their receivers must detect the small target signal in the presence of the inevitable leakage from the transmitter, which is typically many orders of magnitude larger. Unlike the target signal, this feedthrough has no Doppler shift, but its large magnitude can easily saturate the receiver. For example, for a transmitter power level of, say, 100 W (or 20 dB above a watt, +20 dBW) and a receiver sensitivity of −160 dBW, one must achieve isolation of the receiver from the transmitter of 80 dB in order to live within a receiver dynamic range of 100 dB. This isolation is very difficult to realize when transmitted and received signals flow through common sections of waveguide (albeit in opposite directions).

If receiver saturation from feedthrough can be overcome, the radar is then faced with the problem of noise. No microwave oscillator generates a perfect sine wave. Deviations from the ideal may be thought of as frequency sidebands (usually called noise sidebands) on the desired pure tone. When feedthrough or clutter signals are present they will carry these sidebands, which may appear in the Doppler spectrum and, hence, compete with the target signal (Fig. 3). As a result, a CW radar (or, to a degree, any Doppler radar) fights a continuing battle to minimize noise in the transmitter and in receiver oscillators used to heterodyne (or convert) the received signal down to intermediate frequencies.

Unlike noise, birdies are coherent unwanted signals (i.e., having a sinusoidal waveform) that may be introduced by harmonics of power supplies, by microphonics arising from resonant mechanical elements, or as "beat" frequencies resulting from mixing processes (Fig. 4). When these birdies are in the parts of the Doppler spectrum of interest, they may be detected and interpreted by the radar as target signals. Since they are internally generated, they are obviously of no value for missile guidance.

Implementation Problems

In the 1940's these fundamental problems began to be understood, but the state-of-the-art made it difficult to obtain satisfactory solutions. The microwave sources of that time — primarily magnetrons — were quite noisy (although perfectly satisfactory for conventional noncoherent pulse radar operation). Raytheon was the leading producer of magnetrons in World War II by virtue of its development of the magnetron lamination fabrication technique that made quantity production of radars possible. Raytheon was therefore in a good position to address this noise problem, but it proved to be a difficult one.

The receiving vacuum tubes available at that time were large (and microphonic) and Raytheon turned its extensive experience in this area to reducing noise.

When World War II ended, and the urgency in developing an immediate solution to low-flying aircraft disappeared, the effort continued at a reduced level. Workable, though often makeshift, solutions were developed in 1950 that resulted in a small radar that would fit into the 17-in. diam Lark, which had been relegated to an experimental test-bed missile and that at last worked well enough to permit flight tests to be conducted (Fig. 5). The first successful interception of an unmanned F6F drone aircraft was made on Dec. 2, 1950. Even though the flight was a "turkey shoot" — the target was flying straight with no maneuvers, at an altitude well above clutter — it represented a remarkable achievement and was a historical first.

There were several such flights before the first interception of a target in a clutter environment some two years later. Dur-

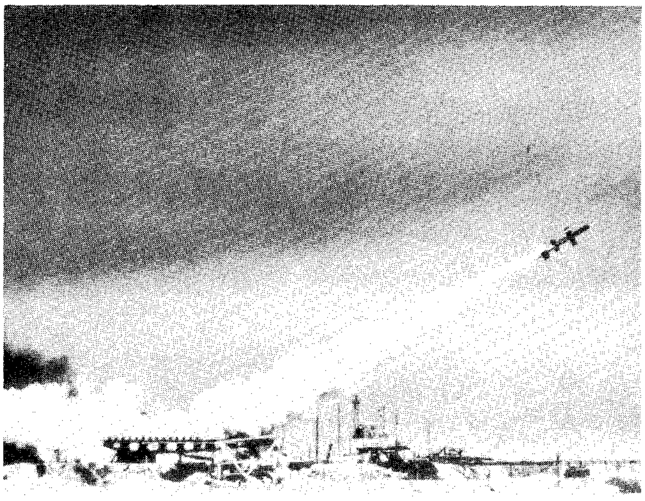

Fig. 5 Lark missile.

ing that time improvements continued to be made and tested. I remember viewing impressive ground-to-air tests conducted from Laguna Peak overlooking the Navy test center at Point Mugu, California, in which the radar smoothly tracked the target aircraft as it dove toward the ground providing a severe clutter background. I probably remember these tests because I was told that I was seeing something that ordinary radars could not do.

The importance of the physical environment (particularly vibration) in those days is illustrated by the lock-on range achieved by the radar. In ground-to-air tests in which the radar was solidly mounted on Laguna Peak, about four-mile range was achieved against an F6F aircraft, which was used as the standard target in the 1950's. In "captive" flight tests in which the radar was carried by another aircraft, a range of about two miles was achieved. And in free flight aboard the missile, about one mile was achieved. Fortunately, one mile was sufficient to make successful live intercepts.

The Sparrow Missile

Primarily as a result of the successful 1950 flight test, the Navy gave Raytheon a contract to put its guidance system into an air-to-air "Sparrow" airframe (Fig. 6). There were already two Sparrow designs: the Sperry Sparrow I (with radar beam rider guidance), which became the Navy's first operational missile; and the Douglas Sparrow II with active pulse radar guidance provided by Bendix.

The Raytheon design, the Sparrow III, differed in a very important way (and with major implications for the future) from the radar successfully flight tested in Lark. It was decided to take the transmitter out of the missile and leave it in the launching aircraft. This "semi-active" guidance, in which only the receiver of the radar is carried in the missile, solved in one step the most difficult design problems of the active CW radar.

By separating the transmitter from the receiver by miles rather than inches (and removing common sections of waveguide through which both transmitted and received signals must flow), the feedthrough and associated noise problem were reduced by orders of magnitude. The maximum transmitter power level that could be tolerated in the active radar (a few watts) was correspondingly increased by orders of magnitude, and, combined with the much larger antenna in the aircraft used to illuminate the target, provided sufficient tracking range to permit homing all the way at the required flight ranges.

The existence of three versions of Sparrow gave the Navy the luxury of selecting the best of three fundamentally different competing design concepts. In the end, the Sparrow III was selected because it was a homing missile that worked, and not because of its low-altitude capability. The beam rider that guided Sparrow I, which came to operate reliably in flight, could not achieve the small-miss distances required for high lethality at the longer flight ranges desired by the Navy. The active Sparrow II was not selected because the technology of the 1950's was not adequate to support the required transmitter power levels in a small missile.

It is somewhat ironic that in the first tactical application of Sparrow III on the McDonnell F3H-2 aircraft, the radar energy for missile homing was obtained by injecting the output of the CW magnetron into the antenna of a conventional pulse radar. Thus, although the missile had an excellent capability against low-flying targets (as was demonstrated in a dramatic interception conducted over San Nicholas Island off Point Mugu in 1954), there was no weapon system capability because the aircraft radar was unable to detect or track targets in a clutter background.

The Hawk Air Defense System

It was about this time, however, that a new opportunity arose to advance the state-of-the-art in low-altitude air defense. The U.S. Army had started a new activity known as "Project Hawk," which was intended to develop the technology needed to provide a battlefield surface-to-air missile (SAM) to protect friendly troops from attack by low-flying aircraft. The Army held a symposium on low-altitude guidance at Redstone Arsenal, Alabama, in early 1953 and Raytheon was invited to present a paper. As reported in some detail in Ref. 1, a paper was presented by T.C. Wisenbaker[2] showing how both clutter and image (or multipath) problems could be overcome with a semi-active CW radar homing missile. As a result of that paper, the Army awarded Raytheon a 10-month contract to perform 13 "critical tasks" considered essential to the successful development of the low-altitude missile system. The tasks succeeded in pushing missile-guidance technology a little further forward, but the major accomplishments lay in the demonstration of the ground support equipment.

Before a missile can be launched against a low-flying aircraft, the aircraft must be detected and tracked to maintain illumination during missile flight for semi-active homing. Thus, the problems of an active Doppler radar, which had been a struggle in Lark and side-stepped in Sparrow, came to the fore again. It was clear that the best hope for success lay in separating the transmit and receive functions (as done in semi-active missiles) as much as possible. Thus, the "two-dish" radar was born. Under the direction of Project Engineer Donald Banks, a missile receiver with a separate 24-in. diam antenna was mounted piggy-back on the 48 in. transmitter antenna (Fig. 7). This provided an isolation of the receiver from the transmitter of about 80–90 dB, considerably greater than the 70–75 dB limitation caused by reflections from nearby objects when the main beam intercepted ground.

Although somewhat of a jury rig, this worked well enough to demonstrate the feasibility of detecting and tracking targets in clutter with an active ground-based CW radar, and helped immensely in convincing the Army to award the contract for developing the Hawk system to Raytheon in June 1954. The radar design was modified in the development program to have two 4-ft-diam dishes side by side on a common pedestal, the configuration that is still used today (Fig. 8). The transmitter selected for the tactical radar was a 200 W magnetron stabilized by an external cavity. By this stabilization technique, tendencies of the magnetron to change frequency are countered by a reactive component of the impedance reflected from the cavity. Stabilization factors of 7–10 were achieved in this manner, sufficient to reduce noise to an acceptable level. In addition to the illuminator, a continuously rotating CW acquisition radar was designed with similar electronics but using two 8-ft-long antennas mounted above each other. This radar continuously scanned the horizon, provide the initial acquisition of targets in clutter needed to start the engagement process. Meanwhile, changes were made in the electrical design of

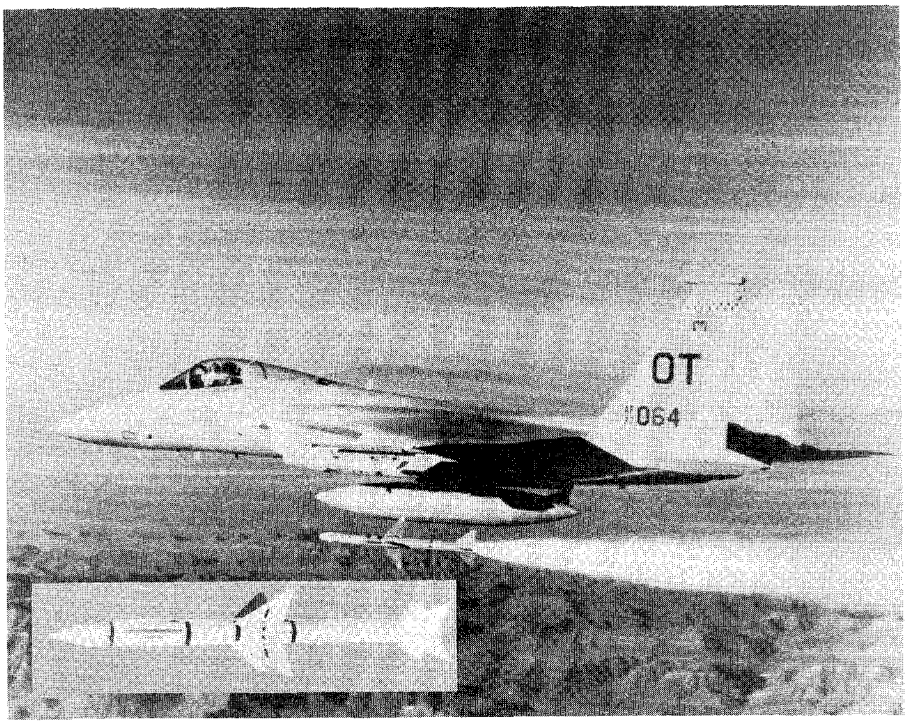

Fig. 6 Sparrow missile.

Fig. 7 Hawk experimental tracking illuminator.

the tracking radar to improve performance, taking advantage of the additional space and complexity possible in a ground-based radar as compared with a missile.

Radar Technology Advances

The limitations placed on the Sparrow missile due to the lack of a Doppler radar in the mother aircraft were felt more acutely because of the success of Hawk in its CW ground radars. The Hawk solution of separating transmitting and receiving functions with separate antennas is not suited to an aircraft radar because of the limited frontal area available in high-speed military aircraft. What was needed was fundamental solutions to all of the original Lark radar problems. These problems was tackled head on by Dr. Harold Rosen, who conceived an ingenious solution to each of them.

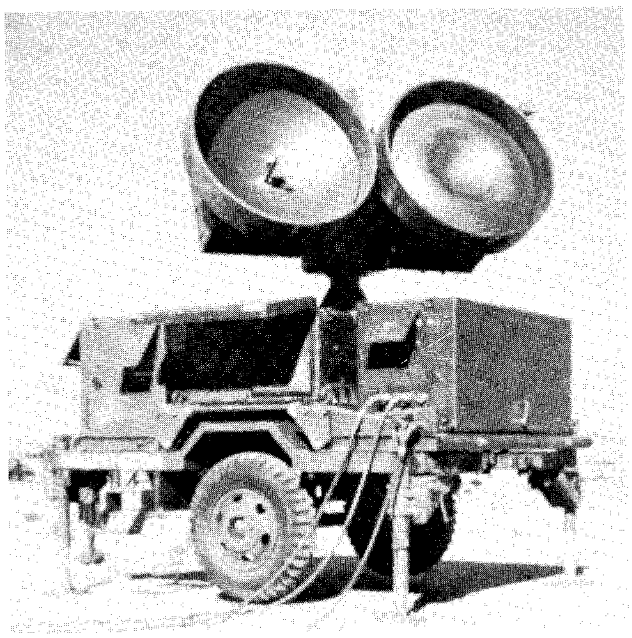

Fig. 8 The improved high-power illuminator (IHPI).

The most fundamental problem was feedthrough. If a single antenna is to be used, a way must be found to radically reduce the amount of transmitter power that leaks into the receiver. After considering and rejecting all brute-force isolation techniques, Rosen decided that feedback was the only way to solve the problem. Using the newly available ferrite devices, he developed a system called "feedthrough nulling" (cf. Ref. 3) that purposely leaks transmitter power into the receiver under the control of ferrite rotators (Fig. 9). The key is that the ferrites were controlled to leak transmitter power of the correct

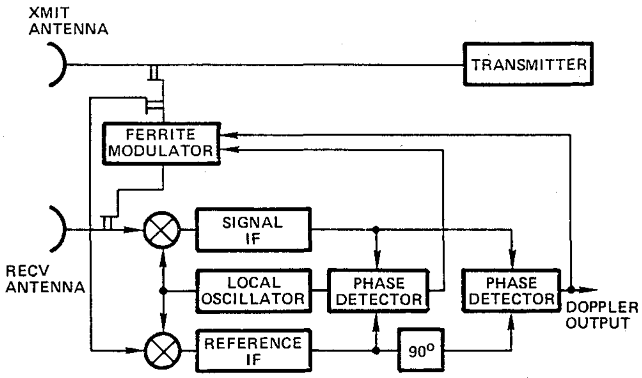

Fig. 9 Feedthrough nulling block diagram.

amplitude and phase to balance out the power that was inadvertently leaking in. Thus, by nulling techniques, using phase detectors to sense the remaining feedthrough, the feedthrough could be reduced to the extent of the gain in the loop.

The close-out or stop frequency of the feedthrough nulling loop had to be kept below the Doppler band of interest to not cancel out target signals; transmitter noise in the Doppler-frequency band in the severe vibration and acoustic environment of an aircraft noise remained a difficult problem. To solve it, Rosen employed noise cancellation techniques, also based on feedback principles. The transmitter was stabilized by purposely modulating the output of the klystron master oscillator to null out the inadvertent modulation (Fig. 10). Operating in a manner similar to that of feedthrough nulling, the resultant modulation was sensed as in-phase and quadrature unbalances in a microwave bridge, with a mechanically tuned cavity serving as the stable reference.

Although these were major steps forward in CW radar design, they were not enough to overcome the severe aircraft environmental problems. Other noise sources, such as reflection of the transmitted power from the aircraft radome, modulated by vibration of the radome, were never completely eradicated. Other techniques were coming into play to allow building a pulse Doppler radar, i.e., one in which the radar energy is pulsed as in conventional radar, but the phase of the rf energy is kept coherent from pulse to pulse to allow Doppler-frequency filtering techniques to be employed. Hughes Aircraft Co. was under contract to the Air Force to develop such a radar, and when the single-dish CW radar efforts did not succeed, Rosen joined Hughes as project engineer on the pulse Doppler radar, ending further airborne CW radar work.

The techniques of feedthrough nulling and noise cancellation, however, were exactly what was needed to build a robust, higher-power version of the Hawk tracking radar. The attractions of CW radar had been recognized by Great Britain, and a number of critical components were being developed by their laboratories. The impetus for a high-power illuminator (HPI), as the radar came to be known, was a 2-kW low-noise two-cavity klystron developed by Ferranti. Although subsequently replaced in the operational design, it (together with the other new techniques) allowed the HPI to be successfully developed and deployed in 1962, replacing the original low-power illuminators in all Hawk systems.

Missile Technology Advances

Let us return briefly to the missile scene. The clutter rejection capability of the original Sparrow (and Hawk) design was about 40 dB and was limited by the dynamic range of the video amplifier that contained the entire Doppler spectrum, including both target signal and clutter. In several Hawk flight tests in 1963 at White Sands Missile Range, the high reflectivity of the lava beds over which the flights were made generated clutter sufficiently high to prevent detection of the target by the missile seeker.

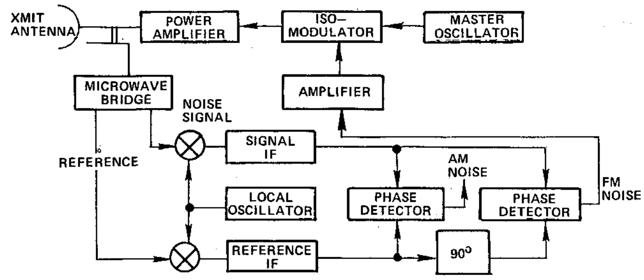

Fig. 10 Noise degeneration block diagram.

A simple modification was adopted that matched the Hawk requirements very well. Frequency shaping was added to the missile video amplifier to attenuate frequencies at which clutter could occur (determined by the maximum velocity of missile, which was accurately known because Hawk, unlike Sparrow, was always launched at the same velocity: zero). This reduced missile sensitivity for tail attacks, where it is not needed, and optimized the clutter rejection for forward-hemisphere attacks, where it is needed. An effective clutter rejection of about 60 dB was achieved by this technique, sufficient to permit successful flights (although at reduced performance) under these severe conditions.

This clutter rejection was limited by the dynamic range of the circuits that must preserve linearity in processing the large clutter signal to prevent the generation of harmonics or other interfering signals. Linearity must be maintained to prevent intermodulation of the large clutter signal causing directional information from clutter to interfere with that of the target. An additional concern with the receiver at that time was its potential vulnerability to electronic countermeasures (ECM). All tracking radars of this period derived their angle tracking information by a sequential process known as concial scanning in which the beam is offset from boresight and scanned in a circle. Targets not directly ahead of the radar cause an amplitude modulation of the received signal, with the amplitude and phase of the modulation determining the target location in polar coordinates. Such a system is potentially vulnerable to jamming, which employs amplitude modulation (AM) at the radar scan frequency, because the radar cannot distinguish this from the AM caused by angle tracking error. Although a semi-active missile retains some protection because it does not broadcast its conical-scan frequency, a more fundamental solution is desired that is immune to jammer modulation.

In the early 1960's a different receiver architecture was conceived that greatly increased the clutter-rejection performance of the missile receivers while also eliminating the ECM vulnerability. This receiver, conceived by Bill Murphy and termed an "inverse monopulse receiver," utilized the newly available crystal filters to accomplish inverse monopulse with almost no increase in complexity compared with the conventional receiver.

As shown in Fig. 11, a three-port monopulse antenna was employed with the outputs representing the sum beam and the two-difference beams (pitch and yaw) that determine the target locations in rectangular coordinates. Following enough fixed-gain amplification to establish noise figure, each output went through an identical 1-kHz-wide filter at the IF frequency. This filter eliminated interfering signals (such as clutter or jammer modulation) that were not within 1 kHz of the desired target signal.

Following the filter, the difference channels were purposely modulated onto the sum signal (as happens in conical scanning) to permit subsequent amplification and processing. Because this is done at a frequency much higher that 1 kHz, there is no vulnerability to amplitude-modulated jamming because AM at the difference-channel modulation frequency is completely removed by the narrow-band crystal filters before the modulation process is employed.

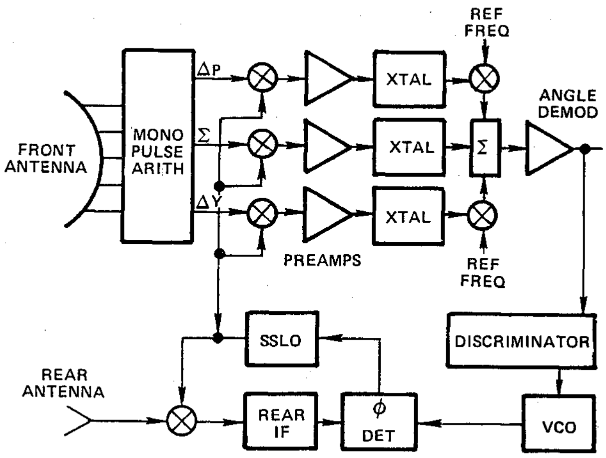

Fig. 11 Inverse monopulse receiver.

This technique also allows all subsequent processing to be done in a single relatively broad channel, eliminating the necessity for the three channels required in a conventional monopulse receiver that must be accurately gain- and phase-tracked relative to each other. Thus, the new receiver had all of the performance attributes of monopulse, although in a much simpler implementation compatible with missile needs. It is inverse in the sense that the narrowest filter is at the front of the receiver rather than the back, which gives it the improved clutter-rejection capability without the necessity for supporting high dynamic range after the channels are combined.

This design formed the basis of the "Improved Hawk" missile program and was later incorporated into Sparrow as well. It is interesting that this innovative concept allowed these clutter and ECM capabilities to be realized in a low-cost missile design at a time when almost all ground-based and aircraft radars still had the limitations of conventional designs, paralleling the history of the initial Sparrow deployment with an incoherent pulse radar.

The Current Scene

In the 1970's the state-of-the-art moved away from CW radar to pulse Doppler (with, it should be noted, monopulse angle tracking). As indicated above, pulse Doppler was a virtual necessity for airborne radars such as those for the F-4, F-14, and F-15 aircraft, which could afford only a single antenna for space reasons (and which could range-gate out the radome to eliminate airflow-induced noise from being reflected into the receiver. It proved equally compelling for the new phased-array radars for ground-based air defense systems such as Patriot, which could afford only a single antenna for fiscal as well as for space reasons. These pulse Doppler radars employ the fundamental techniques developed for CW radars to reject clutter. However, they minimize the problems by opening their receiver only when the transmitter is turned off. On the other hand, it has proven to be much more difficult to achieve low-noise performance in a transmitter that is being turned on and off thousands of times per second. Even with the noise cancellation techniques pioneered in the HPI, transmitter noise is still a limiting factor for some applications.

It should be noted that the application of "stealth" technology to air vehicles may offer a new reason to use CW radar. If the news stories on possible radar cross-section reduction are to be believed, detecting and tracking stealth vehicles at low altitude will require the utmost in clutter rejection, which may be best achievable in ground-based radars with the super stability obtainable with two-dish CW radars and semi-active missiles.

Probably because of the success of Sparrow and Hawk, combined with the increasing popularity of pulse Doppler radar, Raytheon has remained the principal storehouse of expertise in the Western world in CW radars and missiles. Hawk is now used by 21 friendly nations, Sparrow by 20. In addition, the CW technology was adopted by the U.S. Navy for its area defense missiles, originally the 3T's (Tartar, Terrier, and Talos) and currently the Standard Missile. Now built by General Dynamics, the CW technology used in these missiles was originally obtained for the Navy by the Applied Physics Lab. of Johns Hopkins Univ. by purchasing system engineering support and a number of Sparrow seekers for evaluation from Raytheon.

In spite of the increasing popularity of pulse Doppler radars and missiles, CW continues to be widely employed. According to *Aviation Week and Space Technology* magazine, the Soviet SA-6 air defense system employs CW radar homing missiles. The SA-6 has been deployed in the U.S.S.R. since the 1960's and was exported to client states after the Mid-East War of 1967.

Postscript

Doppler radar techniques allow air defense systems to be built that can operate against targets flying against a background of stationary or slowly moving clutter. The original Doppler techniques were employed in CW radars, in principle the simplest kind of radar. Making such a radar operate well in these severe environments required the development of sophisticated technologies for both missiles and their supporting ground radars. Most of this work was performed in the 1950's (and up to the mid-1960's) and was shrouded in secrecy at the time. The present paper has attempted to document some of the interesting (to the author, at least) elements of the work for the benefit of a new generation of engineers who may not be aware of the innovations and excitement of a creative period in air defense system design.

As in Ref. 1, I have relied primarily on my own recollections of the events described. The reader is cautioned that human memory, especially when stretched over a period of several decades, is far from infallible and often embellishes the events being recalled. Nevertheless, since there is no other record of this period of which I am aware, I have done the best that I can.

In the narration I have mentioned a few individuals who made special contributions, even though it is unfair to give them recognition at the expense of others—too many to name—whose engineering skills converted the concepts into operating equipment that worked. The accomplishments described required a dedication of an unusual nature from all involved, occasionally rewarding the participants with great satisfaction, but often including long periods of intense frustration.

In the larger sense, the enterprise reflected the attributes of the society that spawned it. It started, like all innovations, in the mind of one person. It succeeded because that person was able to communicate his zeal and fire to the imagination of other innovative thinkers, who responded with their own zeal, which they in turn passed on to others. The resulting geometric growth led to a collective understanding of the complex problems and to ideas for solutions. Together, the group created a new reality that impacted national and international military policy. It was a collective success that was certainly not foreordained, but one that grew from the individualism of people free to go against conventional wisdom. Bureaucratic authority will always define orthodoxy as the only correct path: nature sometimes disagrees.

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