RCA Engineer

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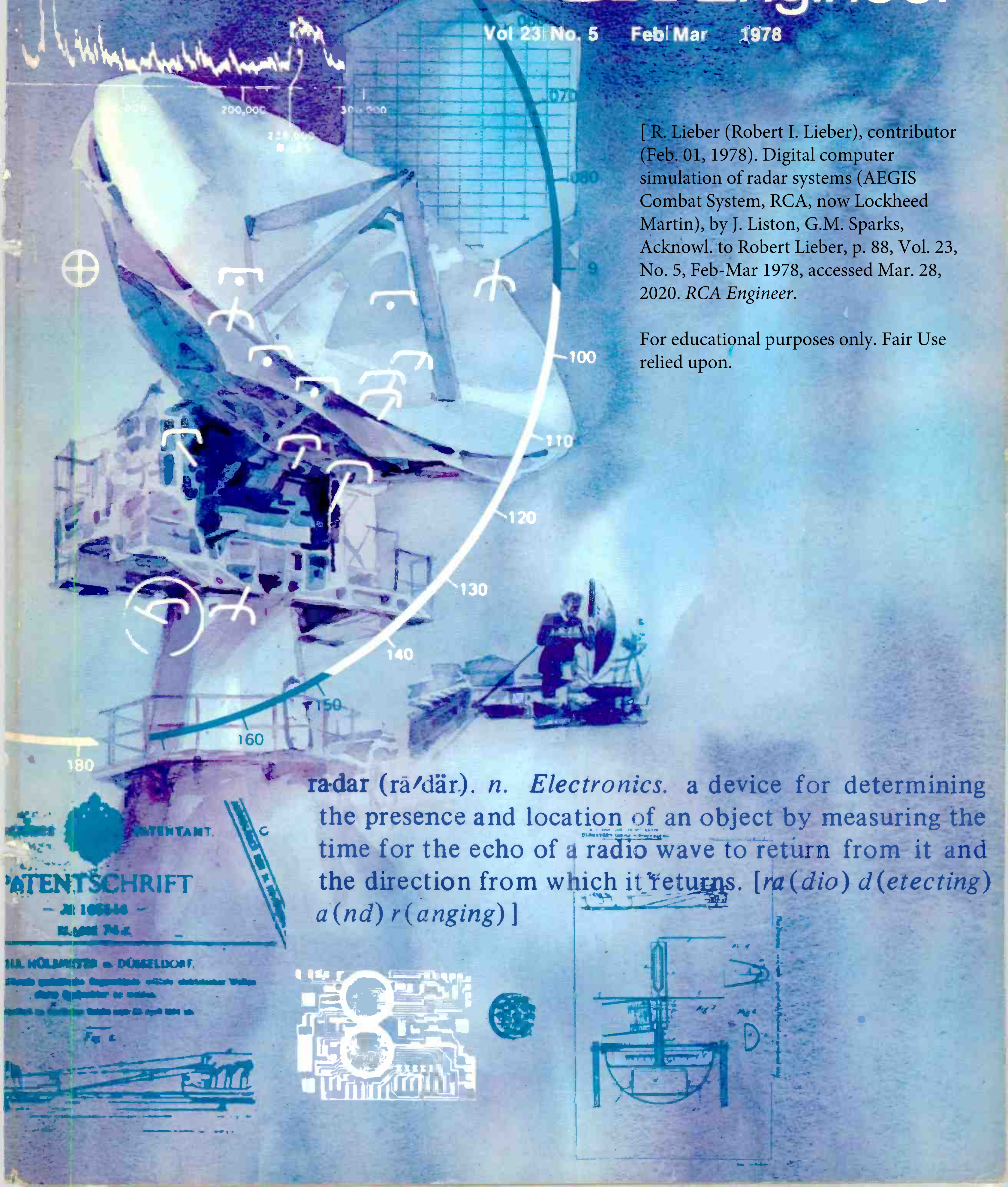

ra·dar (rā′där). *n.* *Electronics.* a device for determining the presence and location of an object by measuring the time for the echo of a radio wave to return from it and the direction from which it returns. [*ra*(*dio*) *d*(*etecting*) *a*(*nd*) *r*(*anging*)]

RCA Engineer

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- To disseminate to RCA engineers technical information of professional value
- To publish in an appropriate manner important technical developments at RCA, and the role of the engineer
- To serve as a medium of interchange of technical information between various groups at RCA
- To create a community of engineering interest within the company by stressing the interrelated nature of all technical contributions
- To help publicize engineering achievements in a manner that will promote the interests and reputation of RCA in the engineering field
- To provide a convenient means by which the RCA engineer may review his professional work before associates and engineering management
- To announce outstanding and unusual achievements of RCA engineers in a manner most likely to enhance their prestige and professional status.

Our cover combines radar's past and present. The large circle is a plan-position indicator showing a number of targets. Starting at the top center of the cover, we have: the trace of the first radar echo bounced off the moon; a face of the AN/SPY-1 phased-array radar system; the AN/FPQ-6 instrumentation radar; Dr. Irving Wolff performing radar experiments at RCA's Camden plant in the 1930s; Hulsmeyer's German and British radar patents from the early 1900s (surrounding modern electronic hybrid microcircuits); Guglielmo Marconi, inventor of the "wireless," shown in two views; a three-dimensional plot of a radar antenna pattern; Heinrich Hertz, who showed that electromagnetic energy could be reflected; an integrated circuit; and Nicola Tesla, who first proposed the practical use of radio waves for detecting objects.

Cliff Winner, from Missile and Surface Radar, Moorestown, N.J., painted the watercolor for our cover.

The radar business—25 years later

Twenty-five years ago, RCA dedicated its new plant in Moorestown on what had formerly been a highly productive asparagus field. This expansion of facilities represented RCA management's long-term investment in the vital field of radar engineering. In his dedicating speech, W. Walter Watts, then Vice President, RCA Technical Products, stated:

> "Radar is but one fast-moving frontier in the amazing science of electronics, which daily brings us new wonders in such fields as television, 'electronic brain' computers, communications, industrial products and controls, and sound recording and reproduction. As in these other fields, we have only scratched the surface of radar's potential services."

That perception has proved to be well-founded. Initially, straightforward applications of traditional radar technology yielded a solid business base in neatly packaged user areas (e.g., the range instrumentation radar "product line"). With the passage of time, technological advances blurred the earlier distinctions between radars, computers, and communications. More importantly, the emphasis shifted from separate electronic "black boxes" to integrated electronic systems. In many cases, radar became the heart of such systems.

At the same time that our customers were demanding ever-increasing levels of performance from radar systems, they have had less money to spend. Thus, "Design to Price" has become a necessity rather than just a slogan.

Today we stand astride a radar technology with capabilities that were beyond conception when Moorestown opened its doors in 1953. Now we can cover the skies from horizon to horizon, detecting, tracking, identifying, and countering everything that moves. Non-military applications also abound, for we can measure ocean wind currents, predict crop yields, and measure soil conditions and potential drought areas all over the world—all with radar. Truly there is reason for pride in accomplishment among radar developers.

And uneasiness, as well. Radar users are becoming increasingly aware of how diverse technologies could converge to extend and expand radar's capabilities. We can be certain that some user, somewhere, is already making far-reaching assumptions on future radar applications. Almost as certainly, some industrial or academic laboratory is nurturing a germ of an idea that will ultimately make these assumptions a reality.

So today the business outlook for radar is as robust as it was 25 years ago. The pattern that has characterized radar development in recent years seems certain to continue. Our challenge is to assure that RCA remains a leader by stimulating and supporting the groundwork of today that will anticipate and satisfy the requirements of the future. Clearly it is a challenge of major proportions.

But it's more fun than growing asparagus.

Max Lehrer

Max Lehrer
Division Vice President and General Manager
Missile and Surface Radar
Moorestown, N.J.

Radar—it's changed

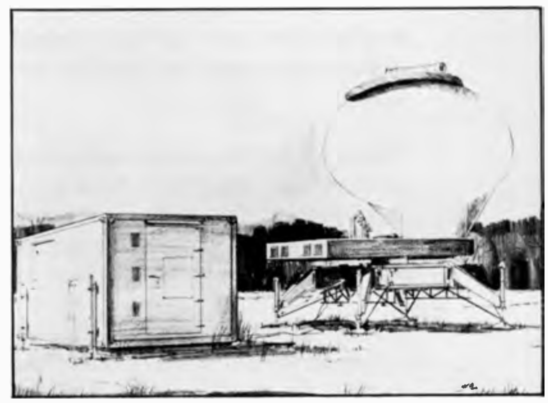
from this

6, 11

to this

25, 32

and this



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Sarnoff Award winners 100

How do RCA's information sources rate?

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coming up

Our next issue (Apr/May) covers the **software** explosion and how it is affecting the traditional hardware-oriented engineer. Our anniversary issue (Jun/Jul) traditionally covers the year's most significant technological events at RCA—**digital television, SOS technology, optical videodisc memory,** and more.

RCA Engineer

Vol. 23|No. 5 Feb|Mar 1978

radar background

radar technology articles

technical excellence

more radar technology articles

on the job/off the job

departments

about this issue...

Radar technology today—perplexity in Wonderland

Part of the wonder and fascination of radar is that it can *do* so much. In something like 40 years, defense establishments all over the world have come to depend on it more and more—originally as a sometimes-reliable sensor, and more recently as a key controlling element in major defensive systems. Today, space-age radars routinely identify, track, and analyze virtually everything in earth orbit.

But the non-military applications of radar are even more exciting. Radar is everywhere—as a bulwark of air traffic control, in marine navigation (including more and more pleasure boats), in assessing soil conditions and crop harvests on an international scale, measuring and plotting terrain features and sea states, and even (as detailed herein) as a tool in the basic steel-production process. Perhaps the best evidence of acceptance is the introduction of the word "radar" into the vocabulary of the consumer products market.

This kind of application explosion didn't just happen. It represents, instead, a studied and imaginative application of modern technology to exploit the intrinsic potential of radar. Practically everything has been tossed into the pot—a broader slice of the electromagnetic spectrum, the wonders of solid-state devices and circuit miniaturization, and the entire range of computer elements. In essence, the continuing growth of radar derives directly from technological diversity.

This kind of diversity, of course, begets *complexity*. And another name for complexity is *perplexity*—for the layman who is struggling to understand, and even to a degree for the trained engineer who knows the basics but is uncertain about how all the peripherals work. The pace of radar development in recent years has opened a very real chasm between the conceptual simplicity and elegance of radar technology and the ability of the average engineer to feel comfortable with it.

A stated goal of the *RCA Engineer* is to help bridge this gap. And this issue represents an honest, if modest, attempt to make some of the technology of modern radar understandable both to those who are interested but not directly involved and to those who are involved, but on the fringes.

Accordingly, the papers in this issue are *not* about RCA products for the most part. Neither do they describe everything that is new and good in the field, either in applications or in the technology.

What this issue *does* offer is a thorough-going primer on radar operation (Barry Fell, p. 14), some interesting historical background and personal reminiscences (Tom Greene, p. 6, and Irv Wolff, p. 11), a summary of where we stand today technologically (Art Robinson, p. 25), and a working-level treatise on the explosion in signal and data processing (Walt Weinstock, p. 32). The remaining papers form a montage of some of the work going on in RCA today—from feeds and antennas, to solid-state switching and amplification, to the dark arts of balancing analog and digital processing techniques, to a few special examples of radar applications.

In summary, although this issue is certainly not comprehensive, it gives a feeling for what radar is all about today. If you see something that interests you and would like to learn more about it, please call one of the authors. They are all articulate and enthusiastic. If you're looking for something and don't see it here, several of the papers include fairly extensive references on specific subjects. And if you're still curious, the following brief bibliography lists a number of recent papers on radar by RCA authors.

Don Higgs
Technical Publications Administrator
Missile and Surface Radar
Moorestown, NJ

Ed. Note: **Don Higgs** presented the idea for the radar issue to the *RCA Engineer* Planning Board in June 1976. He then guided it through several levels of planning and pushed it to its final steps—working personally with most of the authors through rough drafts, rewrites, and approvals. The quality of the result speaks for itself.

Ed Burke, our Consulting Editor at MSR, provided the graphic treatment for Don's Editorial Input.

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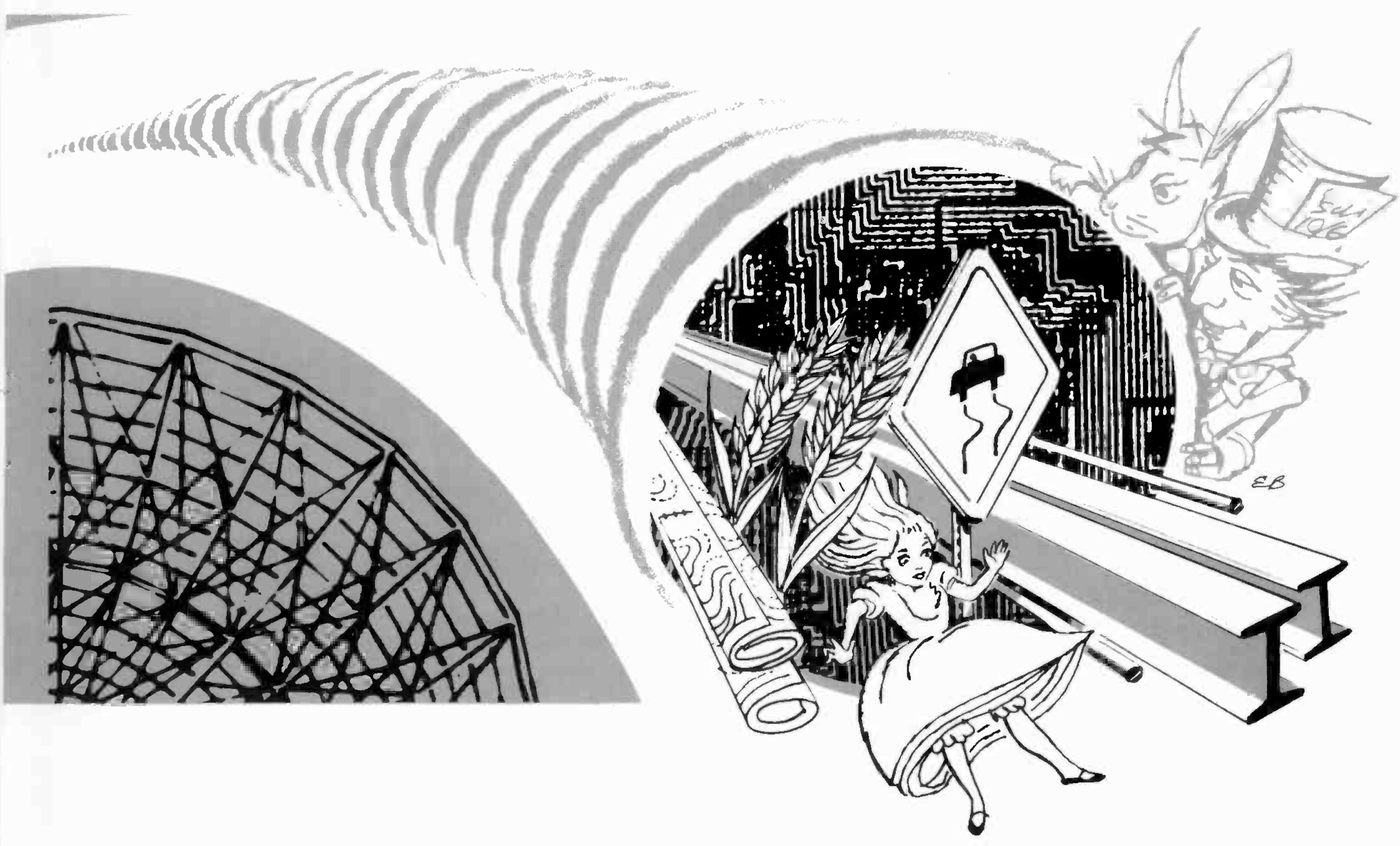


The early days of radar

T.G. Greene

Although the first radar patents were filed in the early 1900s and working systems existed in the 1920s, World War II was the real driving force behind radar development.

Ed. Note: This short history does not attempt to be all-inclusive; it is part of a more complete radar history, consisting of about fifty wall panels being prepared by Tom Greene for display in the corridors of RCA's Moorestown plant. Space constraints have excluded credit to many radar workers within and outside of RCA; we have also stopped our history just after the end of World War II, when large-scale radar-based defense systems entered the scene.

Tom Greene's role here has been that of a collector and editor, rather than as an author. He is deeply indebted to the good memories and collecting habits of the many GSD engineers who helped on this project, as well as those engineers who long ago had the foresight to write thorough final engineering reports on their projects.

1886 Heinrich Hertz

Professor Heinrich Hertz in Germany demonstrated experimentally in 1885 that 66-centimeter radio waves could be formed into beams and that solid objects would reflect them. When the identity between light and radio waves was established, it became clear that a radio wave reflected back on itself would create a wave-interference pattern, and that this pattern would in itself be evidence of the reflecting object.

This wave-interference detection method, the forerunner of the pulse method, was reported by various groups of workers in widely different applications, in the early 1920s, both in the United States and abroad.

1900 Nicola Tesla

When Hertz demonstrated that electromagnetic waves could be reflected by solid objects, he was far ahead of his time in the science of radio-location. It remained for Nicola Tesla to recognize and to point out the practical application of the radio "echo," so vital in the Second World War. Describing his 1889 method and transmission of wireless energy in *Century Magazine* (June, 1900) he wrote:

"Exactly as with sound, so an electrical wave is reflected, and the same evidence which is afforded by an echo is offered by an electrical phenomenon known as a "stationary" wave - that is, a wave with fixed nodal and ventral regions. Instead of sending sound-vibrations toward a distant wall, I have sent electrical vibrations toward the remote boundaries of the earth, and instead of the wall the earth has replied. In place of an echo I have obtained a stationary electrical wave - a wave reflected from afar.

Stationary waves . . . . mean something more than telegraphy without wires to any distance . . . For instance, by their use we may produce at will, from a sending station, an electrical effect in any particular region of the globe; we may determine the relative position or course of a moving object, such as a vessel at sea, the distance traversed by the same, or its speed."

1903 First practical application

KAISERLICHES PATENTAMT.

AUSGEGEBEN DEN 31. NOVEMBER

PATENTSCHRIFT

— № 165546 —

KLASSE 74 d.

CHR. HÜLSMEYER in DÜSSELDORF.

Verfahren, um entfernte metallische Gegenstände mittels elektrischer Wellen einem Beobachter zu melden.

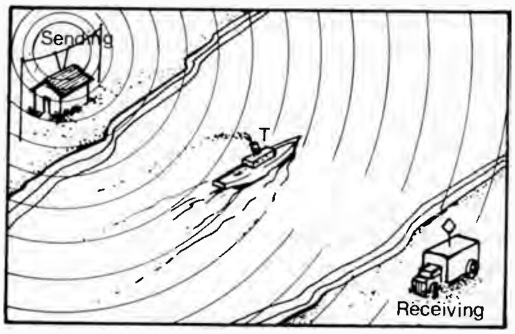
Patentiert im Deutschen Reiche vom 30 April 1904 ab.

Fig. 1.

In 1903 Christian Hülsmeyer experimented with radio waves reflected from ships. He obtained patents in several countries the following year for his obstacle detector and ship navigational device. His scheme was demonstrated to the German Navy but failed to develop interest because the maximum range of detection was only about one mile using the technology available at the time.

Hülsmeyer recognized the problems of stabilizing a highly directional beam on a rolling, pitching naval vessel and provided some correction for this in his British patent entitled *"Hertzian-wave Projecting and Receiving Apparatus Adapted to Indicate or Give Warning of the Presence of a Metallic Body, such as a Ship or a Train, in the Line of Projection of such Waves."*

1922 Ship detection by interference



At the Naval Aircraft Radio Laboratory at Anacostia, D. C., Dr. A. Hoyt Taylor and Leo C. Young were conducting radio field strength measurements when they observed that a ship passing through a high-frequency field affected the performance of the receiver. In September 1922, they suggested the use of this interference effect for the detection of ships.

1924 Watson-Watt and the RAF

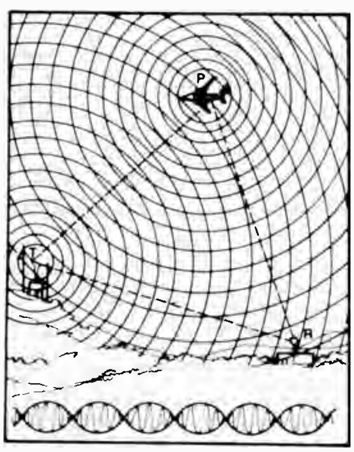
Beginning studies on mechanical direction finders in 1919, Robert Watson-Watt developed a cathode-ray direction finder in 1928 capable of locating thunderstorms out to 400 miles and in azimuth to 1°. With his wife Lady Margaret Robertson Watt as his principal laboratory assistant, he began major research on airplane radio-location in 1935. In 1940-41 the Germans, continually encountering concentrated RAF fighter opposition to their bombing raids, assumed the British had large numbers of fighter planes. At that time woefully weak in fighter craft, Britain was able to vector those they had to the German attackers by using Watson-Watt's equipment.

When Robert Watson-Watt was knighted on King George VI's birthday in 1942, he was identified merely as "a pioneer in radio location." When war security restrictions were later lifted, he finally received credit for his principal role in developing Britain's radar, credited equally with the RAF in winning the Battle of Britain.

1925 Measuring the ionosphere

The first reported use of pulsed radio energy to measure distance was that of Gregory Breit and Merle Tuve of the Carnegie Institute in Washington, D.C. Reporting on their basic scientific investigation in the *Physical Review* in 1926, they described successful efforts to measure the height of the conducting layers in the ionosphere, using interrupted trains of waves (ICW) and an oscillograph to record the echos. Several organizations and amateurs assisted in their experiment. Arrangements were made to transmit from NRL's station NKF, Bellevue, Anacostia, D.C., Westinghouse's station KDKA in Pittsburgh, RCA's station WSC in Tuckerton, NJ, and the Bureau of Standards' WWV in Washington, D.C. Their superheterodyne receiver, located at NRL, used type 201A tubes produced by RCA. The summary of the detailed 21-page paper cited above reported that the hypothesis of an ionized upper layer of the atmosphere was correct and that its height varies from 50 to 130 miles.

1930 Young and Hyland



Leo C. Young and L. A. Hyland, engineers at the Naval Research Laboratory (successor to the Naval Aircraft Radio Laboratory), were experimenting with short-wave direction finding. Hyland noted trouble with the performance of the equipment in the form of occasional violent signal fluctuations. He was ready to return his "balky" receiver to the laboratory for overhaul when he observed that the signal fluctuations occurred only when an airplane flew overhead. Hyland wrote a memo describing this method of detecting aircraft to Dr. Taylor (mentioned earlier), who reported it in a letter to the Chief, Bureau of Engineering, on November 5, 1930. A development program started immediately.

Taylor, Young and Hyland received a patent on a "System for Detecting Objects by Radio" for their NRL work on cw wave-interference radar.

1932 RCA enters the field

Radar research and development were carried on exclusively by the military services until RCA entered the field in 1932, when a group of engineers under the direction of Dr. Irving Wolff began work in the microwave field. Although RCA began radar research and development with marine and aircraft navigation and collision prevention applications in mind, the military applications of radar soon became evident and work with both the Army and Navy followed. (His accompanying article describes this early work more completely.)

By 1937 RCA had developed pulse ranging equipment which could determine the range of a target with considerable accuracy over short distances and obtain reflections from targets at greater distances. A radio detection and ranging equipment installed on the roof of one of the RCA buildings in Camden, New Jersey, was the first microwave pulse radar system in the United States, and probably the world. The antenna was designed with directional characteristics and mounted so that it could be rotated. A cathode-ray tube was employed as an indicator in the receiver output circuit. One coordinate on the indicator tube screen showed distance and a second coordinate showed angle. The skyline of Philadelphia was plotted, and vessels plying the river about two miles distant were located.

1937 Col. Blair demonstrates radar

In 1937, the first equipment developed by the Signal Corps was demonstrated at Ft. Monmouth to the Army Chief of Staff. "General Malin Craig was sold when he saw we were able to keep a plane flying overhead in the beam of a searchlight directed by the radar position finder."

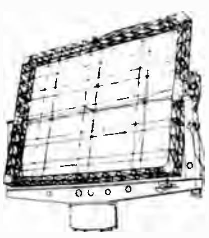
Colonel William Blair did not receive a patent covering the invention until 1957, after special legislation was passed permitting the filing after the legal time limit had expired. Col. Blair could not file until 1945 due to wartime secrecy. His pulse echo system used a single transmitter and receiver to determine distance and direction. The system credited to Sir Robert Watson-Watt of England required two receivers.

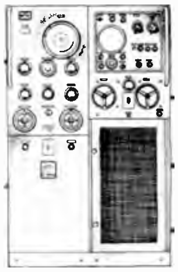
1937 Shipborne radar

In 1937 RCA began work on the development of the CXZ, a shipborne equipment for detection and ranging, operating at 475 MHz. A single cabinet housed the transmitter, modulator, and pulse generator, and also served as a pedestal for the antenna array. This was the first shipborne radar designed by a commercial firm to be installed on a Navy ship, the *USS Texas*.

At the same time a radar operating at 200 MHz was developed at the Naval Research Laboratories and placed on the *USS New York*. Comparative tests of the two equipments showed that the RCA unit had superior definition, while the NRL version gave longer range. A model incorporating the best points of each was designed and RCA received a production contract for six units designated Model CXAM.

1939 Commercial radar for the Navy



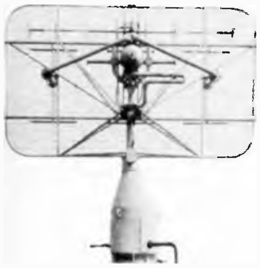


RCA's production contract for six CXAM radars was followed by a contract for fourteen additional equipments known as Model CXAM-1.

The Model CXAM was the first radar produced for the Navy by a commercial firm. It was an air search instrument providing range and bearing information, and was designed for installation on aircraft carriers, battleships, and cruisers. The first of these equipments was installed on the flagship *USS Augusta* in June, 1941. At the time of our entry into World War II, the twenty sets installed on the most important ships of the fleet were the only radars in use by the Navy.

An officer serving on the *USS California* reported using CXAM 1 equipment successfully for navigational purposes on a fogbound trip from Seattle to San Francisco.

1941 High-production shipborne radar



The SA (Shipborne, Surface and Air Search Radar) was developed to provide early warning and keep track of surface vessels and aircraft targets. It also proved useful as a navigation aid. The Model SA was intended for installation on destroyers and destroyer escorts. Development started in April 1941 and the first model was delivered in September. Production started immediately after the Pearl Harbor attack; 1565 sets of the Model SA series were produced by RCA at Camden. This was the largest quantity of this type of equipment produced by any one manufacturer during the war.

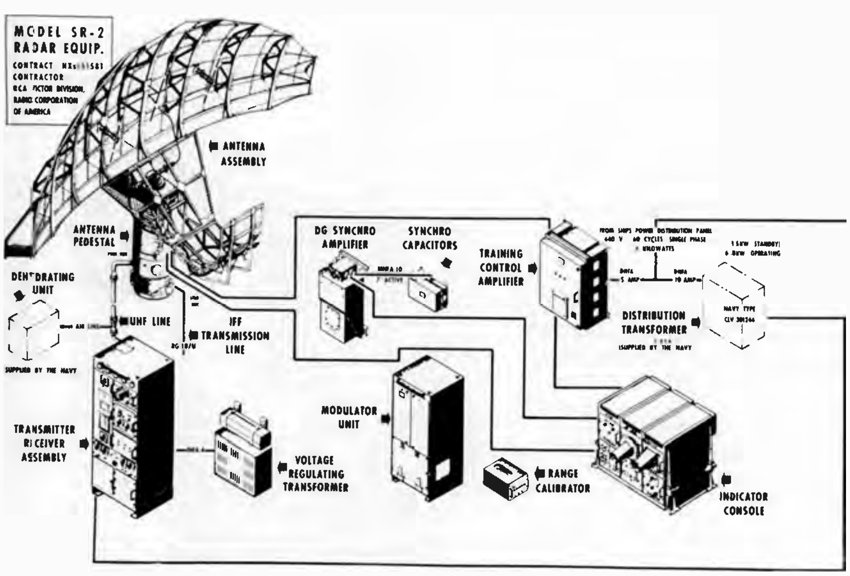
1942 Madam X — the proximity fuze

RCA engineers cooperated with the U.S. Navy's Bureau of Ordnance and the Office of Scientific Research and Development in the development of the proximity fuze for use in rotating projectiles such as field artillery or antiaircraft shells. This fuze was designed to burst in the vicinity of the target, within the fragmentation area of the shells, making it as effective as a direct hit.

Known officially as the VT fuze, it was unknown to all but a few military officials, scientists, and engineers until the war was over. To the factory workers, it was a mysterious project known as Madam X. Five and one-half million fuzes (more than half those supplied to the armed forces between October, 1942 and war's end) were assembled at RCA's Camden, New Jersey and Bloomington, Indiana plants.

The VT fuze was enclosed in the nose of the projectile. A conical metal cap on the tip acted as an antenna. It continuously radiated high-frequency energy in a beam roughly matching the fragmentation pattern of the projectile. When a portion of the radiated field encountered a target, the antenna loading varied, which in turn changed the plate current of the oscillator. This change was detected and amplified enough to start a thyratron tube conducting and so actuated the detonator in the projectile. A special wet battery, in which the electrolyte was contained in a glass ampule, supplied the electrical energy. The shock of firing broke the ampule and the spinning of the projectile distributed the electrolyte through the battery cells. The fuze required the designing of miniature tubes and associated parts sturdy enough to withstand not only the terrific impact when the gun was discharged, but also the centrifugal force of the shell's high-speed spinning.

1943 High-frequency radar



The Model SR-2 shipborne surface and air surveillance radar was designed to incorporate the experience gained on all previous search radars to provide long-range warning for large ships.

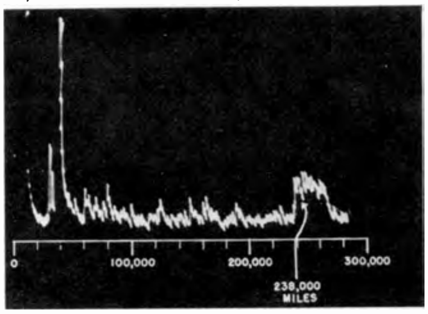
Coordinated design began in October 1943 and the first production model was shipped to NRL for test in April 1945. Two sets were delivered and installed aboard the *USS Midway* and the *USS Franklin D. Roosevelt* before World War II ended. A total of 18 sets were produced by RCA before the program was cancelled at war's end. Operating at a higher frequency than the SA, the SR-2 had a longer range and supplied more accurate range and bearing data than earlier shipborne search equipment. The antenna structure was made of stainless steel to avoid corrosion problems experienced with former search arrays.

1946 Radar echoes from the moon

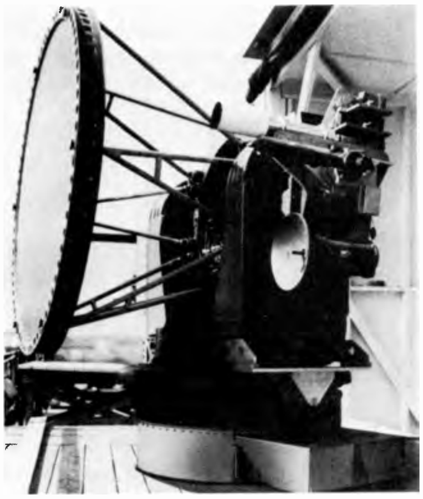
Late in 1945 the U.S. Army Signal Corps began a program to determine whether radar signals could be reflected from the moon and what use might be made of them.

Two antenna "mattresses" of the type used on the Army SCR-270-271 radar were assembled together at Evans Signal Laboratory in Belmar, NJ. The resulting array of 64 dipoles, about 40 feet square, was supported on a 100-foot tower. Because the antenna could rotate in azimuth only, observations were restricted to a relatively short time near moonset and moonrise.

On January 10, 1946, the first echoes from the moon were obtained at moonrise. One of the earliest photographs from these experiments, that of an echo at moonrise on January 22, 1946, is shown on the sweep of a conventional type-A radar oscilloscope. At about 2-1/2 seconds after the first pulse was transmitted, a vertical deflection of the trace occurred — the pulse returned from the moon had been received. This became the most widely published cathode-ray tube trace in history.



1946 Radar systems



The Bumblebee contract was one of the earliest examples of an integrated radar system. The system did far more than detect targets. The contract was initiated to have RCA support the U.S. Navy and their systems contractor, the Applied Physics Laboratory of the Johns Hopkins University. RCA's task included: "Research and development work . . . carried on in connection with electronic guidance equipment for guided missiles . . . . Special emphasis shall be placed on the development of radar equipment to track enemy targets and to guide these (Bumblebee) missiles to the targets."

The significant feature of this contract for RCA was that it led into the entire instrumentation radar business for the corporation: AN/FPS-16, AN/MPS-25, AN/FPQ-4, AN/FPQ-6, AN/TPQ-18, CAPRI, and AN/MPS-36.

Reprint RE-23-5-2
Final manuscript received January 18, 1978

Author Greene holding a prototype four-horn monopulse feed for the Apollo LM rendezvous radar.

Tom Greene's long association with radar began in 1942, when he tested SA, SD, and Mark 11 radars for RCA in Camden. He worked on the AN/FPS-16, Talos, BMEWS, and DAMP programs at MSR and later served as Manager of Proposals and Contract Reports there. He is now an instructor for PRICE, RCA's cost-predicting model, and is also responsible for PRICE documentation.

Contact him at:
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Government Systems Division
Cherry Hill, N.J.
Ext. PY-5782

Radio Vision—the early days of radar at RCA

RCA's involvement in radar started as an attempt to find an application for microwaves.

I. Wolff

Finding work for microwaves

When radar development was first undertaken, mostly by various military establishments, in the middle 1930s, the carrier frequency used for the transmission was several hundred MHz at the high end. It wasn't until compactness and greater directivity indicated the use of a basically higher carrier frequency, and a powerful pulsed magnetron was developed in England, that work on microwave radar started in the early 1940s at M.I.T. Radiation Laboratory.

Irving Wolff initiated the program of microwave research at RCA described in this article that eventually led to the production of radar equipment. He became Director of the Radio Tube Research Laboratory in 1946 and was Vice President, Research, RCA Laboratories from 1954 until his retirement in 1959.

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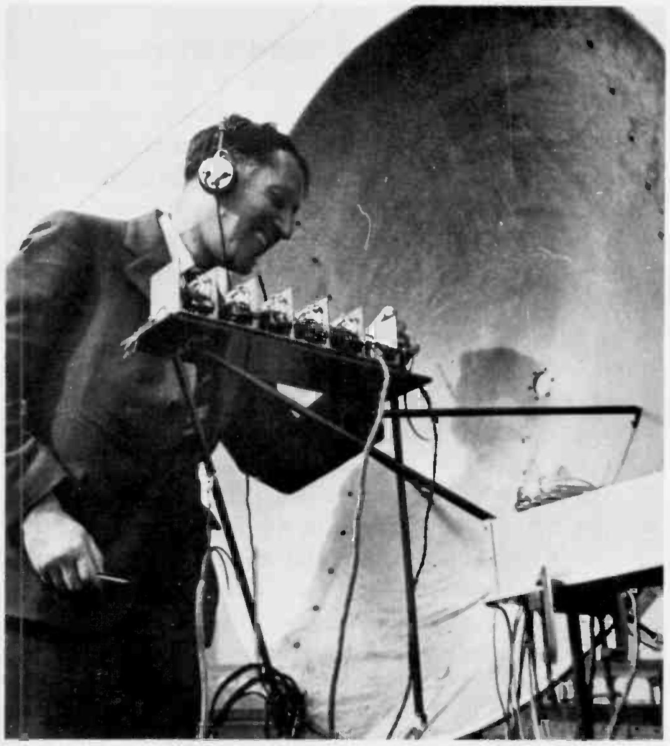
609-924-3252

Author Wolff checking early radar equipment on the roof of Building 5 in Camden during the 1930s.



In RCA, one might say that we had the cart before the horse. In the early 1930s radar, we called it Radio Vision, was initially developed to find an application for microwaves some seven years before microwaves became the backbone of radar.

About 1932 publications were appearing, originating in Germany and Japan, relating to developments of microwave magnetrons. Research was also reported at the University of Michigan. This seemed to be a fruitful area for RCA research, and with the approval of Dr. E. W. Engstrom, Manager of Research, we initiated a program to develop a 3000-MHz system. Dr. E. G. Linder was recruited from Cornell to undertake a magnetron development. The receiver we used first was an old-style silicon-crystal type.

By 1934, work had progressed sufficiently to have an operating transmitter-receiver system and RCA demonstrated the equipment at several IRE meetings during that year. At that time, the possibility of reflecting sharp beams of microwaves from metal objects and ionized gases was shown.

The Signal Corps was excited by these demonstrations and invited us to bring the equipment to Navesink Light at Sandy Hook, N.J. to test the range of the apparatus as a communication set. We were very thankful for this invitation because the location for distance tests was much better than any we had in Camden. The transmitter site was at an altitude of 250 feet overlooking New York Bay and there was a clear range over New York harbor of more than 15 miles. The transmission tests were quite successful, giving a range as great as line-of-sight.

From our standpoint the most significant experiment was an attempt to obtain a reflection from a boat entering New York harbor. The channel was about one-half mile from the transmitting-receiving location and we were elated to receive reflected signals from a ship passing through the channel. Some water tanks on shore at about the same distance were also good targets.

Pulse radar

Our equipment at this stage used audio modulation of the transmitter; three-foot parabolic dishes on both transmitter and receiver obtained directivity. Thus, only the azimuth of the reflecting object was determined. The success of the reflection experiments at the Signal Corps Laboratory changed the orientation of our research from the possible application for radio relaying to use as a navigation instrument. For most effective application in navigation, however, distance as well as azimuth information would be required, leading us to start a project for pulse modulation of the transmitter and pulse amplification in the receiver. We aimed for a pulse of less than one microsecond duration to obtain satisfactory distance resolution.

RCA's Camden plant was the site of early radar experiments.

Apparatus with such pulse modulation was constructed in 1938 and the equipment was placed on the roof of Camden's Building 5 for tests. The receiving equipment was later modified to substitute a superregenerative magnetron for the crystal or detector. We were able to pick up and follow the ferry boats and other shipping in the Delaware River as well as the trains on the elevated line on the Philadelphia side of the river.

At first, we had only a distance trace on the scope with a vertical blip showing the distance of the reflecting object. It was not long, however, before we tied the position of the antenna to the horizontal trace, the time after pulsing of the transmitter to a vertical trace, and the pulse signal to the grid, giving what is now called B scan.

In considering this development, it is interesting to think about the debt we owed television in what we were doing. If it had not been for the television research it is doubtful that we would have had the tubes to amplify the short pulses and the cathode ray tubes on which to show the return signals. These pieces of equipment are so commonplace now that it is easy to forget that they were new developments at that time.

How our radio-vision equipment could have been developed to have a commercial application is anyone's guess. We had in mind using it as a navigation aid installed on ships, and with additional refinement it might well have gone in that direction.

A series of plane crashes gave radar development a push.

However, a seemingly more important commercial need took precedence and changed the direction of our research sharply. Shortly before the time when the successful tests described above were made, there had been a series of very bad airplane crashes into mountains. At a high-level meeting held to discuss the lack of progress that RCA had made toward securing leadership in aviation radio, it was suggested that adopting our radiovision equipment to airborne use as a collision preventive could give us a big boost with the airline industry. This was the kind of imaginative technological advance using radio techniques that appealed to General Sarnoff, and we were directed to see what we could do.

The project, initiated in the spring of 1937, was oriented to the development of airborne equipment which would warn pilots of the approach to mountains and other aircraft. Owing to the instability, research nature, and antenna bulk at that time, a practical airborne system seemed doubtful until microwave components had gone through a development phase. Hence, the highest frequency which could be used with existing commercially available components, 500 MHz, was chosen for the radio frequency of the airborne equipment. We did not have manpower available to continue research on both the existing 3000-MHz project and the new airborne unit, so the former was temporarily set aside.

In the latter part of 1937, the new equipment was installed in RCA's Ford Trimotor airplane and numerous flight tests were made during the ensuing year. Targets were the Catskill Mountains and the Alleghenies of Pennsylvania. Two antenna systems were employed. To get a signal from potential obstacles in front of the airplane, we used an inverted "V" type antenna installed along the length of the Ford airplane. A dipole antenna under the plane obtained the altitude signal. With the airplane in level flight at the height of the mountain top, signals were received at a distance of about 5 miles. If the airplane were 1500 to 2000 feet above the mountain no signal was visible. The signal picked up from the ground reflection on the dipole altitude antenna was always visible. Other airplanes flying up to one-half mile directly in front of our radar-equipped plane could be detected. This was probably the first successful airborne radar equipment flown anywhere.

It had been our intention to give public demonstrations of our apparatus, as well as a modification of it for shipboard use to guard against collisions with other ships and obstacles such as icebergs. But once more, our plans had to suddenly change. By the late 1930s, war clouds were thickening in Europe and the military personnel who were shown the equipment and results immediately clamped a lid of secrecy on it and gave us contracts to develop apparatus for their use. Thereafter we became essentially a government contractor.

In summary, some seven years after it had been first undertaken, our microwave research led indirectly to first development, and later manufacturing, contracts for various types of radar apparatus for the military. Directly related to the airborne equipment which was demonstrated was a search radar using a Yagi antenna mounted on the wing of PBR flying boats and a high-altitude altimeter to aid in accurate high-altitude bombing.

It was entirely fortuitous that we just happened to have something very much needed by the military at the right time and it is interesting to speculate as to what might have happened if war had not been on the horizon. Assuredly, military application had not been our objective when we started the microwave research, or even when "Radio Vision" was well along. One can certainly say that progress in development and manufacture would have been much slower without the impetus of R&D funds and the urgency of equipment for a war.

FM radar

This, so far, has been the story of our early pulse radar. However, "circumstance of location" led us into another use of reflected radio waves using frequency modulation of the carrier (now known as fm radar).

At about the time we were making the flight tests in the Ford Trimotor, a young man contacted our patent department and said that he had some equipment to demonstrate. C. D. Tuska and I went to look. This was the "circumstance of location" referred to above. If the young man, Royden Sanders, had not happened to live close to Camden, it is very doubtful that RCA would have undertaken any fm radar research at that time.

While a sophomore at engineering college, and unaware of the Bell Laboratories fm radar work, Sanders independently developed the concept of fm radar and left college to work on his idea. We were familiar with the Bell Laboratories work and noted that he appreciated some of the factors which limited accuracy and had taken steps to make needed improvements in his development. We were sufficiently impressed to offer to buy whatever improvement patents he might obtain and to give him a chance to proceed with his development in RCA. This proved to be a wise decision. Sanders turned out to be a prolific and determined inventor as well as a sound engineer with a great dedication to fm radar.

RCA's fm-radar altimeter was very accurate at low altitudes.

In due course, a development model of an altimeter was built and demonstrated to the military services. This altimeter was not competitive with our high-altitude bombing pulse altimeter, since the pulse unit was most useful at then high altitudes such as ten to twenty thousand feet, where the ambiguity caused by pulse length was not of primary importance. On the other hand, the fm unit was most useful at low altitudes even down to fifty feet or less. When the fm altimeter was put into production, some tens of thousands were produced and, most unusually, the same apparatus was standardized for the US Navy, the Air Force, and the British. The production demands and timing were too great for RCA to handle alone, so two additional manufacturers were recruited to build the same unit.

The fm-radar altimeter proved to be most useful over water, where its exceptional low-altitude performance could be well put to use. As a next step, the output was tied in with the aircraft altitude control to set the altitude automatically. Since the output of the fm altimeter is most readily a current proportional to altitude, this step was not too involved, at least to the extent of getting adequate control signal from the altimeter.

The next step was a single radar that provided altitude, distance, and speed of approach.

Although it was obvious that the fm radar signal contained the information for determining the distance to the reflecting object, it was not generally appreciated that it also contained information on the speed of approach to the reflector. Sanders appreciated that where there was relative motion between the radar and the reflector, the sum of the up-sweep and down-sweep output frequencies gave a signal proportional to distance, whereas the difference was proportional to speed of approach to the reflector. Thus, the information required to drop a bomb in level flight over water, namely altitude, distance, and speed of approach to target, were all available from one instrument. One antenna pointed forward to get the target information and a second antenna pointed downward to obtain altitude measurement.

Equipment for dropping bombs automatically was constructed and numerous flight tests were made dropping water bombs against the lighthouses in Delaware Bay. Fortunately, none of the numerous fishermen in small boats in the river was ever hit.

A final step was to adopt the equipment to automatic bomb release in other than level flight. Before the more sophisticated development could be completed and put into production, though, the war was over.

This completes the story of the early days of radar (Radio Vision) in RCA, a project which was initiated to develop equipment and study applications of microwaves, and ended by supplying search radar, radio altimeters, and automatic bomb-dropping research and apparatus to a military at war.

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An introduction to radar concepts

B. Fell

Radar is basically simple—transmitting a pulse of microwave energy at a target and timing the reflected return. But the radar designer must produce equipment that can also detect the valid signals in a noisy environment, separate target signals from clutter, and avoid antenna-induced errors.

The origins of radar (RAdio Detection And Ranging) science are obscure, since early attempts to detect objects with radio waves ended either in failure or uncertainty as to the usefulness of this phenomenon. As discussed in Skolnik,[1] although pulsed radar was used as early as 1925 to investigate the ionosphere,[2] the earliest radars used to detect aircraft were bistatic continuous wave (cw) systems.

Early radars were used to detect the presence of targets but, as pulsed radar techniques were developed, radars were able to determine target slant range, angle, and rate of change of slant range with respect to the radar.

With the advent of short-wavelength radar ($\approx$ 1 cm to 3 cm) and miniaturization of electronic components, radar was placed aboard aircraft. Present-day airborne radar is used for avoiding collisions with other aircraft, determining aircraft altitude, locating areas of extreme turbulence, such as weather fronts and thunderstorms, and controlling onboard weapon systems, such as guns or missiles.

The primary military use of radar during the 1950s was to detect and help identify aircraft. Two North American air-defense systems built at that time were the U.S.-Canadian DEW (distant early warning) Line along the arctic circle and the U.S. SAGE (semi-automatic ground environment) radar net within the continental United States.

The Soviet Union's launching of Sputnik I in October 1957 called for the development of high-power, land-based, long-range radar that could probe the environs of outer space. The U.S. Ballistic Missile Early Warning System (BMEWS) and the Space Detection and Tracking Network (SPADATS) were developed and deployed over the last 20 years to answer ballistic-missile and satellite-defense problems.

Pulsed-radar functions are also being performed by optical systems, made possible by the development of the pulsed laser over the past 15 years. Optical radar is sometime referred to as ladar (LAser Detection And Ranging).[3]

Table 1 indicates the standard frequency bands allocated to microwave radar. Long-range (greater than 100 nautical miles) radars normally operate within vhf, uhf, or L-band. S- and C-band radars operate over medium ranges (50 to 100 nautical miles). X- and K-band systems are usually limited to short ranges (less than 30 nautical miles) since their transmissions experience high attenuation as they propagate through the earth's atmosphere. The microwave absorption is mainly caused by oxygen and water vapor in the atmosphere.

Table I

Radar frequency bands are allocated internationally by the International Telecommunication Union (ITU). Atmospheric attenuation increases with frequency, so low-frequency radars are used for long-range operation and high-frequency radars for short-range missions.

Letter Designation	Frequency
VHF	137 – 144 MHz 216 – 225
UHF	420 – 450 MHz 890 – 940
L Band	1215 – 1400 MHz
S Band	2300 – 2550 MHz 2700 – 3700
C Band	5255 – 5925 MHz
X Band	8.5 – 10.7 GHz
K_u Band	13.4 – 14.4 GHz 15.7 – 17.7
K Band	23 – 24.25 GHz
K_a Band	33.4 – 36 GHz

This paper deals exclusively with radar that operates in the microwave region of the frequency spectrum. It should provide a brief answer to the questions:

1) What is a radar?

2) How does a radar work?

3) What are the analytical tools used in radar system design?

Types of radar

Radars perform two primary functions: surveillance and tracking.

Surveillance (or search) radars, such as the RCA AN/UPS-1 and the GE AN/FPS-24, search a volume of space and report the detection of targets within the volume. Most airport radars are of the surveillance type. Tracking radars determine a time-history of and Tracking System (SPADATS), in the late 1960s, doubled the United States space-tracking ability.

and the Sperry AN/SPG-55, must be provided with initial pointing data in order to acquire and lock onto a target. The target is tracked until it leaves the radar coverage, maneuvers out of the radar tracking "gate," or until the target is no longer of interest. Tracking radars have been used at such facilities as Cape Canaveral, Wallops Island, and the Pacific Missile Range.

Many radars perform both surveillance and tracking. Included in this group are: 1) track-while-scan radars; 2) track radars that have a search capability; and 3) agile-beam radars.

A track-while-scan radar produces track data by correlating detection reports as the radar scans continuously in angle. The correlation procedure can be accomplished by a sophisticated computer or an operator seated at a display.

Tracking radars, such as the RCA AN/FPS-49, which can open their tracking gates to detect targets over a wide range interval, are able to search a volume of space. Once a detection is made, the radar can position its antenna beam in the direction of the target and execute a tracking algorithm. This type of system is usually unable to track more than one target.

Agile-beam (or inertialess beam-steering) radars have been made possible with the introduction of electronic, as opposed to mechanical, beam steering. Although electronic beam-steering techniques were used to a limited extent during World War II, the full advantages of inertialess beam steering were not realized until the early 1960s. Agile-beam radars have the flexibility to schedule search or track functions in any direction as needed, since their antennas are not constrained to rotate at a fixed rate (if indeed they rotate at all).

The RCA shipboard AEGIS AN/SPY-1 radar system is an example of an agile-beam radar. AN/SPY-1 uses a two-dimensional array of phase shifters to steer the radar beam. Hence it is called a phased-array radar. The AN/SPY-1 maintains a volume search and, upon detecting a target, tracks that target while still maintaining the volume search. The AN/SPY-1 can thus track many targets anywhere in its detection volume and still perform surveillance of the radar coverage.

Since time is a fixed entity, an agile-beam radar must trade off available time between search and track functions. However, the data-handling capabilities associated with an agile-beam system can be enormous. For instance, the addition of one Bendix AN/FPS-85 phased-array radar to the USAF Space Detection and Tracking Systems (SPADATS), in the late 1960s, doubled the United States space-tracking capability.[4]

Radars can also be characterized by the types of data they collect. Five common types of radar are continuous-wave, pulsed, pulsed-doppler, multistatic, and synthetic-aperture systems.

The continuous-wave (cw) radar transmits a continuous signal. If this signal is transmitted at a fixed frequency, target doppler (a measure of the target speed along the line connecting the radar location with the target position) can be determined very accurately. Many police departments use this type of radar to monitor the speed of automobiles. In addition to target doppler, frequency modulation provides a method of determining target range with cw radars.

Pulsed radars transmit a fixed duration pulse of energy at repeated intervals called the pulse repetition interval (PRI). Pulsed radars measure target range and angle.

Pulsed doppler radars measure target position in the same manner as pulsed radars but, in addition, extract doppler information from a received train of pulses. The doppler and position information is used not only to detect and track targets, but also to discriminate between moving targets and radar clutter. The remainder of this paper concentrates on describing the properties of pulsed doppler systems unless stated otherwise.

Multistatic and synthetic aperture radar systems will be discussed briefly for the sake of completeness.

Multistatic radar uses one or more transmitters and a set of radar receivers over a long baseline to provide highly accurate angle, as well as range, information. If the elements of the multistatic system are coherent, a multistatic radar becomes a microwave interferometer. The multistatic concept has been used extensively in the field of radar-astronomy.

Synthetic-aperture systems provide high angular resolution with small antenna apertures. Interferometric in nature, these radars are placed on moving platforms such as aircraft or satellites and use the platform motion to simulate a set of receive antennas.

Barry Fell is a physicist who has worked in the areas of phased-array radar and radar electronic countermeasues. Since joining the Systems Department of RCA Missile and Surface Radar in 1976, he has been engaged in the development of ultra-high reliability, low-prime-power-consumption, unattended radars for use in remote locations.

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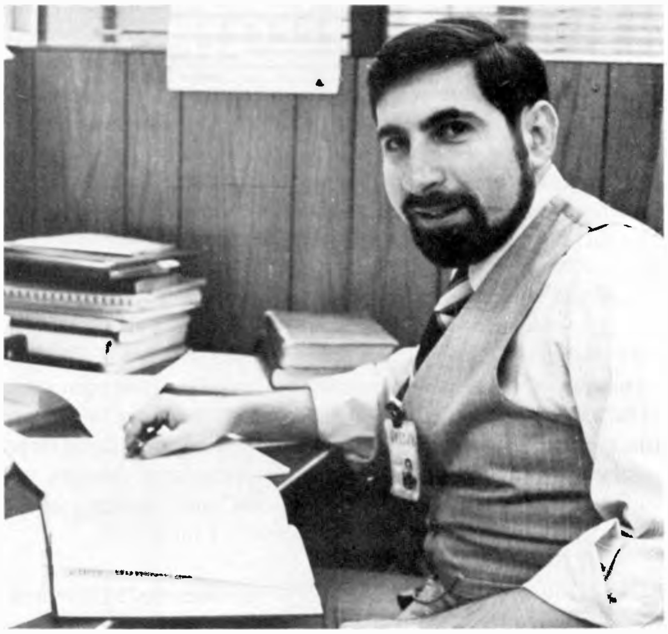

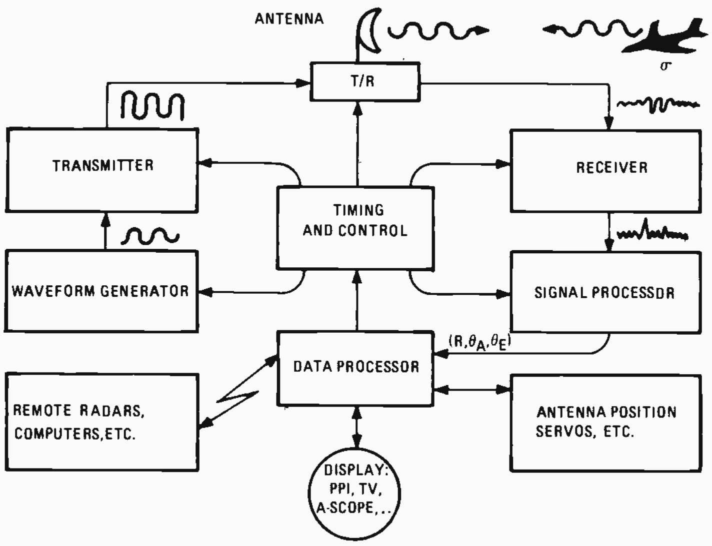

Fig. 1
A radar consists of a number of subsystems that affect overall system performance, but are all tied to a central timing/control subsystem. The waveform generator produces a pulse that is amplified by the transmitter and radiated by the antenna. If the pulse strikes a target, a return (dependent on the target's radar cross section) will be reflected back to the antenna. This signal is amplified in the radar receiver; the *S/N* is maximized by a technique known as matched filtering. The signal processor takes this information and filters out unwanted returns. A data processor provides for the radar's long-term timing and control, sending signals to display units, the antenna positioners, to other radars or computers, etc.

Radar functions

Radars can detect targets, estimate target position and velocity, and identify targets.

Target detection consists of searching a volume of space and reporting any targets which appear in that volume. Target position and velocity estimation includes the determination of range, angle (either azimuth, elevation, or both) and range rate (doppler) with respect to the radar. Target velocity cannot be measured instantaneously by a single radar, but must be derived from a time history of target position data.

Radars that measure target range, azimuth, and elevation are called three-dimensional; radars that measure range and only one angle are called two-dimensional. A two-dimensional system which measures range and elevation is sometimes called a height finder, since it provides an accurate determination of target altitude.

There are two general approaches to target identification: Selective Identification Friend/Identification Friend or Foe (SIF/IFF); and Space Object Identification (SOI). SIF/IFF is a technique in which a radar sends out a coded series of pulses that in turn trigger a transponder carried aboard the radar target. The transponder reply is directed toward the radar and contains target information such as target identification, range, and altitude. Air-traffic controllers at major airports use such systems to immediately identify aircraft in the vicinity of the airport.

SOI is a radar identification technique that uses the "skin return" from a radar target. Over the past 20 years, much progress has been made in identifying orbiting satellites by illuminating these radar targets at high data rates. The resulting amplitude vs time history of the target returns is analyzed to determine target characteristics such as size, shape, and tumbling rate.

Radar system operation

As shown in Fig. 1, a radar is composed of a series of subsystems: a waveform generator, a transmitter, an antenna, a receiver, a signal processor, a data processor, control equipment, and displays.

The waveform-generator produces a pulse of electromagnetic energy.

This pulse, the beginning of the radar cycle, can be a simple sinewave at a constant frequency or a complex waveform. Typically, complex radar waveforms may include a series of subpulses at the same or varying frequencies, a single phase-coded pulse, or a single frequency modulated (fm)-coded pulse.

The transmitter is an amplifier that increases the amplitude of the waveform generator output to the desired level.

This amplification is accomplished at radio frequencies (rf) by either a magnetron, klystron, traveling wave tube, conventional microwave tube, or solid-state power amplifier. The transmitter is characterized by its power amplification (gain), peak power output, pulsewidth, and duty factor (product of transmitted pulse duration and the pulse repetition frequency). The output of the transmitter is fed to the antenna subsystem.

The antenna matches the impedance between the guided-wave output of the radar transmitter and the free-space propagation of the radar pulse.

Antennas are of many types and sizes. The antenna determines the two-dimensional beamshape and beamwidth of the transmitter radar energy. Since the antenna concentrates the transmitted energy in a particular solid angle, passing energy through an antenna amplifies the total radar energy in a particular direction as opposed to transmitting radar energy equally in all directions. This characteristic of an antenna is called the directive gain. Antenna gain and beamshape are discussed below.

If a radar target is passive (i.e., if it does not actively produce radio transmissions that are directed back to the radar), the target merely acts as reflector that intercepts a portion of the transmitted radar power and reradiates it in various directions. These reflection characteristics are described by the target radar cross section (σ).

A radar target can modify the radio frequency of the transmitted radar waveform.

The component of target velocity along the propagation direction of the radar transmission (v_r) shifts the frequency of the transmitted pulse, because of the doppler effect, according to the relation

$$\Delta f = 2\, v_r/\lambda \qquad (1)$$

where Δf is the magnitude of the frequency shift and λ is the wavelength of the transmitted pulse.

The radar mission determines the radar operation after transmission of a pulse. Surveillance radars continually scan a volume of space. The antenna beamwidth, antenna scan rate, and pulse-repetition frequency of such a radar determine the number of pulses transmitted and hence received by the radar. A typical search radar may transmit 20 pulses during the time it takes the antenna beam to sweep across a target. Tracking radars, on the other hand, know the target position relative to the beam axis, and by means of feedback they can continually steer the antenna so it is always directed towards the target.

The radar energy reflected from a target and captured by the radar antenna is sent to the radar receiver.

The receiver subsystem converts the frequency of received energy from radio frequency (rf) to an intermediate frequency (if), which is usually around 50 MHz. The receiver amplifies the received energy and maximizes the signal-to-noise ratio of individual pulses through a technique called matched filtering. This information is sent to the signal processor, which interprets the content of the received energy.

The signal-processing subsystem filters out unwanted returns.

Such unwanted "clutter," is typically energy reflected by obstacles on land, the land itself, the sea, or precipitation in the form of rain or snow. The signal processor can perform coherent or non-coherent pulse integration and presents its output to an indicator screen or an automatic target-detection subsystem.

A timing and control subsystem oversees overall operation of a radar during the period from pulse formation to pulse formation.

Overall radar operation is controlled by an operator or, in modern high-data-rate automatic systems, by a data processor. In addition, the data processor performs data smoothing and prediction for targets under track. The data processor also compensates for platform motion associated with radars located aboard aircraft or ships.

Radar output goes to a display or as control information for other systems.

The output of the radar can be presented in various ways, such as: 1) a plan position indicator (PPI) scope, which plots target range versus antenna azimuth position; 2) an "A"-scope, which displays receiver output amplitude as a function of time (i.e., range) for a particular azimuth or elevation direction; or 3) a cathode-ray tube (CRT) display updated by a data processor in real time. The radar system can use its output data to position its own antenna or drive also be sent to distant command and control posts, other computers, or to other radars. For example, a multistatic radar network requires communication among the related sensors to enable maximum use of the information obtained from the extended radar baseline.

Radar detection of targets

Detection can be broken down to transmitting a pulse, receiving a return, and separating signals from noise.

A radar determines the basic target-position parameters by producing a high-powered pulse of microwave energy (Fig. 2). This pulse energy is concentrated into a beam and directed by the radar antenna into a solid angle centered along a line in space. If a target lies in the general direction of this beam, the target will intercept and reradiate a portion of the transmitted radar energy.

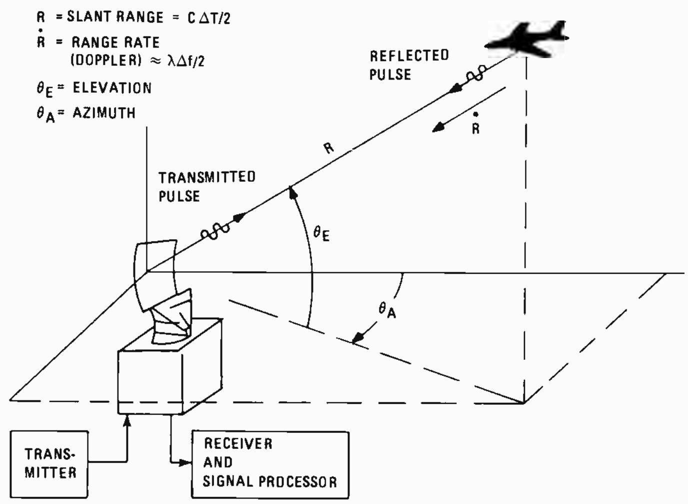

Fig. 2
Target positions can be determined in terms of slant range, azimuth, and elevation (for a "3-D" radar) or range and only one angle ("2-D" radar). Range is determined by timing the interval it takes for a pulse traveling at the speed of light to travel to the target and back. Range rate is derived from the doppler-induced frequency difference between the transmitted and received pulses. Coarse angle measurements are obtained from the antenna pointing direction.

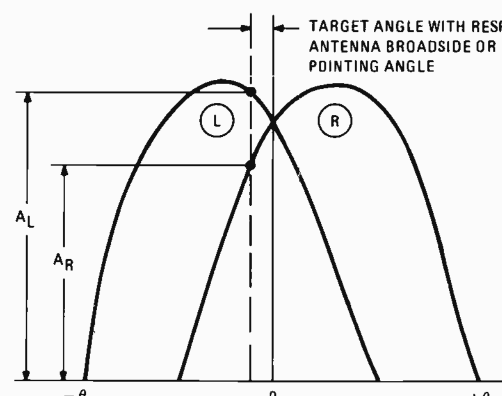

Fig. 3
Fine-angle measurements are obtained by comparing the returned target amplitude (and/or phase) in two adjacent beam positions. These beams are generated either electronically or by physical movement of the antenna. The ratio of the received target amplitudes in the left and right beams is used to measure the target position with respect to the antenna broadside or average steering angle.

The radar antenna captures a portion of this reradiated energy and sends it to the radar receiver/signal processor where the presence of the target is detected, assuming the returned signal strength can be differentiated from the system noise and clutter.

The slant range from the radar to the target is determined by measuring the time delay between the transmission of the pulse and the detection of the echo. The rate of change of this slant range with respect to time (which is called the range rate or doppler of the target) is determined by measuring the frequency difference betwen the transmitted and received pulse.

The target angular position is determined from the antenna pointing direction. Fine-angle information can be determined in many ways, all of which essentially compare the target amplitude and/or phase in two adjacent beam positions. These beam positions are generated either simultaneously (monopulse) or sequentially (sequential lobing). See Fig. 3.

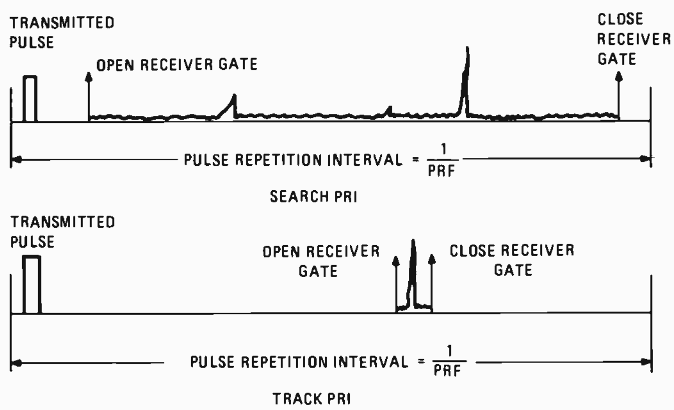

Fig. 4
Radar pulses are transmitted at a fixed rate—the pulse repetition interval (PRI); its reciprocal is the pulse repetition frequency (PRF). A search radar (top) is interested in the entire volume it is searching, and so monitors returns throughout the radar's entire range. A tracking radar (bottom), however, is interested only in the target it is tracking and so only monitors returns about the target's estimated position.

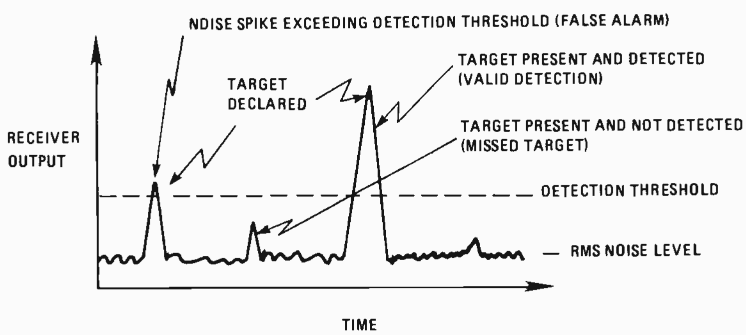

Fig. 5
Detection threshold is a variable. It is set to produce the best compromise between avoiding false alarms and avoiding missed targets.

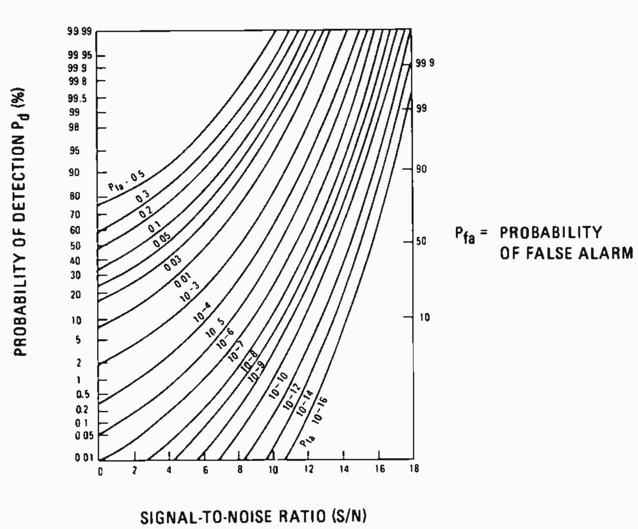

Fig. 6
Detection probability and false-alarm probability vary with *S/N*. Threshold setting must take this into account.

As mentioned previously, target detection is performed in the radar's receiver and signal-processor subsystems. The radar receiver must differentiate the reflected radar signal from the system noise background. The received signal strength depends on the target range and reflection characteristics, the radar transmitting power, and antenna gain. System noise is caused by unwanted electromagnetic energy that either enters the radar antenna from the radar environment or is produced by brownian motion of electrons within the radar receiver itself.

The radar transmits pulses of electromagnetic energy at a fixed rate called the pulse repetition frequency (PRF). As illustrated in Fig. 4, the time interval between two successive pulses is called the pulse repetition interval (PRI), which is the reciprocal of the PRF.

The receiver in a search radar monitors energy which has entered the radar receive antenna throughout the radar's entire range. See Fig. 4(top). The receiver in a tracking radar, however, monitors received energy only over the range extent which brackets the target's estimated position. See Fig. 4(bottom).

Target detection consists of establishing a threshold and declaring a target when a returned pulse of energy exceeds that threshold.

The detection threshold (Fig. 5) can be manually controlled from a gain control on the operator display, or it can be set automatically either at a fixed level or at a variable level based on a constant-false-alarm-rate (CFAR) logic network. The presence of noise makes target detection a statistical problem. The probabilities associated with target detection in a noise environment are:

1) *probability of false alarm*, which is the probability that a noise spike will exceed the preset threshold;

2) *probability of detection*, which is the probability that a target return, if present, will exceed the threshold; and

3) *probability of a missed target*, which is the probability that a target return will not exceed the threshold.

For a mathematical introduction to the detection of signals in noise, the reader is referred to section 2.5 of Ref. 5.

Fig. 6 plots detection probability versus signal-to-noise ratio for various detection threshold settings (i.e., for various probabilities of false alarm).[6] For a given threshold (probability of false alarm), the greater the signal-to-noise ratio, the greater the probability of detection. Similarly, for a given detection probability, the higher the threshold setting (i.e., the lower the probability of false alarm) the greater is the required signal-to-noise ratio.

The radar range equation

The signal-to-noise ratio (S/N) and system false-alarm probability (P_{fa}) determine the probabilty of detecting a radar target (P_D), i.e.,

$$P_D = P_D\,(S/N,\ P_{fa}) \tag{2}$$

In addition, the signal-to-noise ratio developed on a target along with an associated resolution factor determines the estimation accuracy for the target range, range rate (doppler), and angle with respect to the radar. The estimation accuracy standard deviations, σ_R, $\sigma_{\dot{R}}$, and σ_θ, are given by the relations:

$$\sigma_R = \Delta R / [k_R\,(S/N)^{1/2}] \tag{3a}$$

$$\sigma_{\dot{R}} = \Delta\dot{R}/[k_{\dot{R}}\,(S/N)^{1/2}] \tag{3b}$$

$$\sigma_\theta = \Delta\theta/[k_\theta\,(S/N)^{1/2}] \tag{3c}$$

ΔR, the radar range resolution, is determined by the reciprocal of the effective bandwidth of the transmitted pulse. $\Delta\dot{R}$, the radar doppler resolution, is determined by the reciprocal of the effective time the target is illuminated by the radar. $\Delta\theta$, the angle resolution, is determined by the antenna effective beamwidth. The constant factors k_R, $k_{\dot{R}}$, and k_θ are determined by the relation between the transmitted waveform, the filter response of the receiver, and the antenna beam characteristics.

The radar range equation represents the relationship between the received radar signal-to-noise power ratio and a series of parameters which characterize the radar, the target, and the environment.

The radar range equation can be written as

$$S/N = (P_{peak}/kT\,B\overline{NF})\,(G_T)\,(\sigma/4\pi R^2)\,(A_e/4\pi R^2)\,(1/L) \tag{4}$$

where

(S/N)	is the signal-to-noise ratio at the output of the radar signal processor;
P_{peak}	is the peak power transmitted by the radar;
k	is Boltzman's constant;
T	is the ambient temperature (degrees absolute);
B	is the bandwidth of the radar receiver;
$\overline{NF}$	is the noise figure of the receiver;
G_T	is the transmit antenna gain;
R	is the slant range from the radar to the target;
σ	is the radar cross section of the target;
A_e	is the effective area of the receive antenna; and
L	is the total system losses.

The radar range equation provides an analytical tool for analyzing and predicting radar performance. As shown in Eq. 4, the radar range equation determines the instantaneous signal-to-average noise power as a function of the radar and target parameters.

As shown in Eq. 5, the signal power present at the output of the radar receiver (S_{out}) is determined by the peak power transmitted by the radar, the antenna gain provided by the radar upon transmission of the signal (G_T), the ratio of the effective target radar cross section area (σ) to the area over which the transmitted energy has spread ($4\pi R^2$), the ratio of the effective receive antenna aperture area (A_e) to the area over which the reflected energy has spread (also $4\pi R^2$), times the gain of the receiver (G_A), divided by the system losses (L).

$$S_{out} = P_{peak}\,G_T\,(\sigma/4\pi R^2)\,(A_e/4\pi R^2)\,G_A\,(1/L) \tag{5}$$

The environmentally-caused noise within the receiver bandwidth B at absolute temperature T is

$$P_N = kTB \tag{6}$$

where k is Boltzman's constant, a universal constant that relates temperature to energy. The noise figure of the receiver ($\overline{NF}$) is a measure of the noise produced by the receiver itself. It is defined by the relation

$$N_{out} = kTBG_A\,\overline{NF} \tag{7}$$

where N_{out} is the total noise output generated by the receiver and G_A is the gain of the receiver. Therefore, the signal-to-noise ratio present at the receiver output, the ratio of Eqs. 5 to 7, is described by Eq. 4 above.

The radar antenna receive power gain, G_R, is related to the effective area of the radar antenna, A_e, through Eq. 8,

$$G_R = 4\pi A_e/\lambda^2 \tag{8}$$

where λ is the free-space wavelength of the transmitted radar signal.[7]

The antenna effective area, A_e, is related to the physical area of the antenna, A, through the expression

$$A_e = \rho\,A \tag{9}$$

ρ is called the antenna efficiency factor. Its numerical value is between zero and one. The efficiency is a function of: 1) the efficiency with which the antenna aperture is illuminated; 2) the amount of energy which "spills over" the edges of the aperture (and is wasted); and 3) the efficiency of the antenna feed.

Solving Eq. 8 for A_e, substituting this result into Eq. 4, and combining terms gives the following form of the radar range equation:

$$S/N = P_{peak}\,G_T\,G_R\,\lambda^2/\,[(4\pi)^3\,R^4\,(kT)\,B\,(\overline{NF})L] \tag{10}$$

The radar range equation shows which system parameters the radar designer can control.

The peak transmit power (P_{peak}), antenna gain (G_T,G_R), transmit wavelength (λ) and receiver bandwidth (B) are parameters which are under the control of the radar systems designer.

The system designer has limited control over receiver noise figure ($\overline{NF}$) and system losses (L). Low noise figures can be achieved by using cryogenic techniques or, more practically, by using parametric amplifiers as the receiver first stage. Principal system losses include: 1) losses in the radar waveguide on transmit and receive; 2) propagation losses caused by atmospheric attenuation; and 3) signal-processing losses. The atmospheric noise temperature (T) is dictated by the radar environment. The radar cross section of the target (σ, which is not necessarily equal to the physical cross-sectional area of the target) is specified when stating the radar performance requirements for target detection. However, the actual radar cross section of a target depends on the target size, shape, and aspect angle with respect to the radar line of sight.

The peak power, P_{peak}, refers to the power produced when the transmitter is turned on for the duration of the pulse, τ. The average transmitter power during a pulse, P_{avg}, is given by the relation

$$P_{avg} = P_{peak}\,(\tau/T) \tag{11}$$

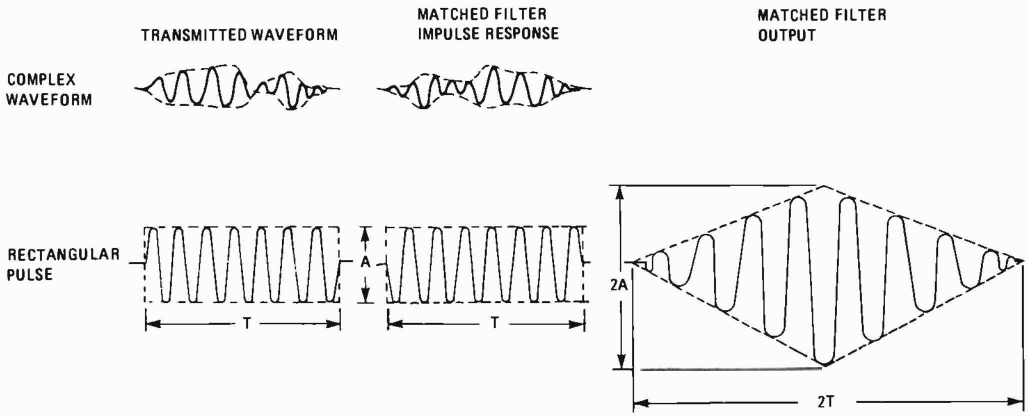

Fig. 7
Matched filtering between transmitted waveform and receiver output produces the maximum S/N. It does not preserve the shape of the original transmitted pulse as seen with the example of the rectangular pulse.

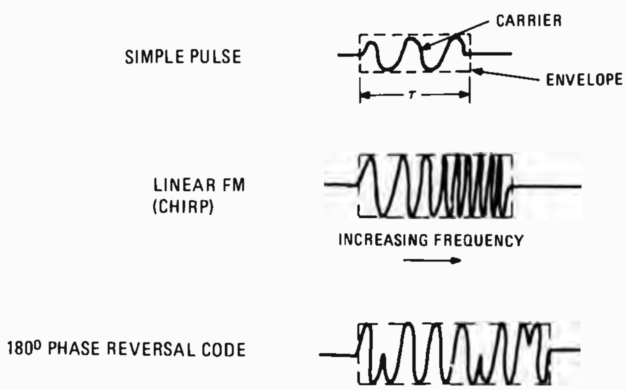

Fig. 8
Typical radar waveforms. Simple pulse is formed by rectangular modulation of the rf carrier. "Chirp" waveform, used to achieve high range resolution at moderate transmission power, is actually a long pulse generated by delaying different frequency components of a short pulse. Phase-reversal codes are used to obtain pulse compression for low as well as high time-bandwidth products.

where T is the pulse repetition period. Since $T = 1/PRF$, the relation between average and peak transmitter power can also be written as

$$P_{avg} = P_{peak}\,(\tau)\,(PRF) \tag{12}$$

The transmitter duty factor (DF) is defined to be the quotient of the average transmitted power to the peak transmitted power, hence

$$DF = P_{avg}/P_{peak} = \tau\,(PRF) \tag{13}$$

Continuous wave (cw) radars transmit a continuous "pulse" at a fixed frequency. Under these conditions $\tau \rightarrow \infty$, $PRF \rightarrow 0$, $P_{avg} = P_{peak}$, and thus $DF = 1$.

Signal-to-noise enhancement

The matched filter is the first step in S/N enhancement.

The signal-to-noise ratio at the receiver output is maximized when the receiver is a matched filter with respect to the transmitted radar waveform.[8] The impulse response of a matched filter is the time reversal of the transmitted waveform, as illustrated in Fig. 7. The matched-filter output is the convolution of the transmitted waveform with the matched-filter impulse response. Matched filtering does not preserve the original transmitted pulse shape. For example, the matched-filter output associated with a rectangular-pulse transmitted waveform is a triangular pulse, as shown in Fig. 7.

The selection of the transmitted waveform used by a radar system is based on factors such as required range and doppler resolution, peak power constraints, and clutter environment. Fig. 8 illustrates a few typical radar waveforms. A simple pulse transmitted by a radar is formed by rectangular modulation of the radio-frequency carrier. The pulse shown has a pulse length τ.

Transmitted waveforms can have internal codes. For example, a long pulse generated by delaying different frequency components of a short pulse (pulse expansion) before transmission and delaying the frequency components in an inverse manner upon reception (pulse compression) is called a "chirp" waveform. The chirp pulse provides the equivalent of a high-power illumination of the radar target using only a moderate peak transmission power because of the length of the transmitted waveform. At the same time, the chirp pulse provides high range resolution, which is determined by the effective bandwidth of the pulse.

Pulses can also be coded by periodically shifting the transmitted radio frequency phase 180 degrees, as illustrated in Fig. 8. The matched filter for this type of phase code has an impulse response equal to the time reversal of the transmitted phase code.

Pulse trains are used to determine target doppler as well as target range. Since doppler resolution is determined by the reciprocal of the effective time the target is illuminated by the radar, multiple pulses transmitted in a single pulse repetition interval can be used to make a gross doppler determination during that period. Fine doppler estimates can be made by processing a series of pulses transmitted over a sequence of pulse repetition intervals. A series of pulse repetition intervals that are processed as a group to enhance target detectability constitute a dwell of the radar beam. See Fig. 9.

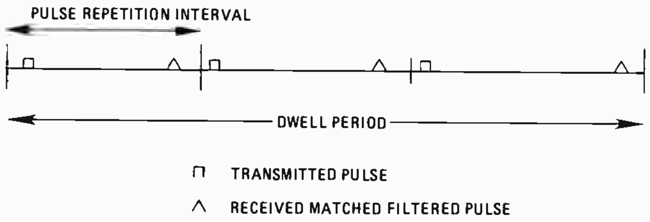

Fig. 9
Radar "dwell" enhances target detectability by processing a series of pulses.

Table II
Radar returns for a target usually vary from pulse to pulse because of the complicated reflection process taking place. The fluctuating radar cross section for different target types was initially categorized by Swerling. His Models I and III usually apply to jet aircraft or missiles, while Models II and IV apply to propeller-driven aircraft.

CROSS-SECTION DISTRIBUTION	SWERLING MODEL	PULSE-TO-PULSE
EXPONENTIAL – RANDOM ASSEMBLY OF REFLECTORS	I	COHERENT
	II	NON-COHERENT
RICE – ONE LARGE STEADY AND NUMEROUS RANDOM REFLECTORS	III	COHERENT
	IV	NON-COHERENT

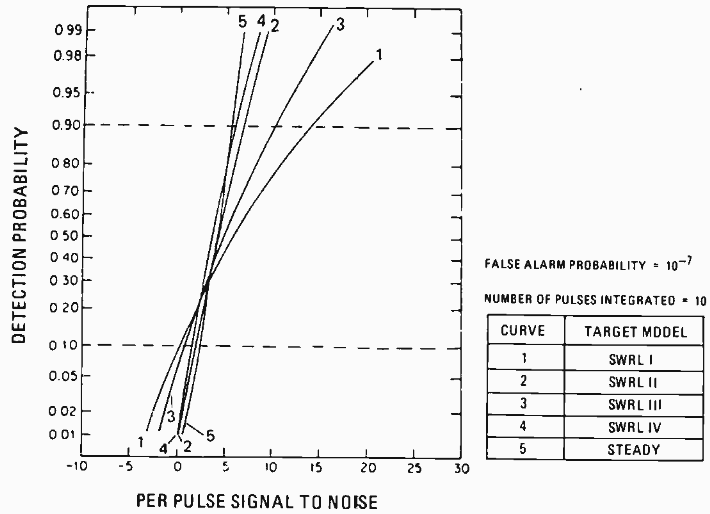

Fig. 10
Detectability varies with type of target model. Example here assumes false-alarm probability of one in ten million and that 10 successive pulses have been integrated. Note that detection-probability curves for fluctuating targets and steady targets cross as *S/N* increases.

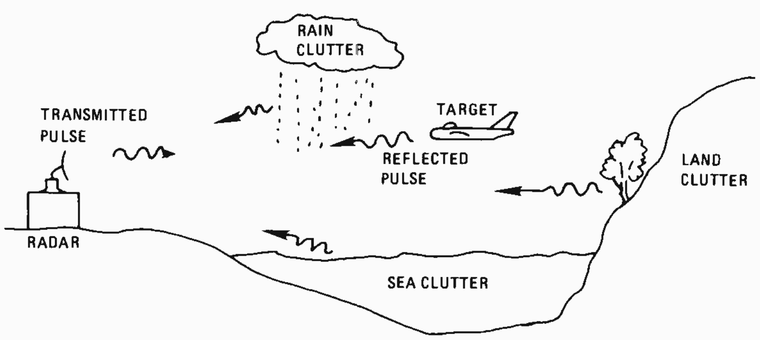

Fig. 11
Clutter is radar energy returned from objects other than the desired target.

The signal-to-noise output of a radar system can also be enchanced by integrating a series of radar returns.

The integration, which is performed in the signal processor or data processor, effectively multiplies the single-pulse signal-to-noise ratio by a factor n_e. Hence,

$$(S/N)_{integrated} = n_e\,(S/N)_{single\ pulse} \qquad (14)$$

where n_e is equal to the number of pulses integrated (n) if the integration process is coherent over the integration period. If this coherence is disturbed or not present within the radar system, n_e is a number between $n^{1/2}$ and n, depending on the system factors that affect the integration process.

Coherent integration depends on the coherence of the radar transmitter, the target reflections, and the receiver characteristics from pulse to pulse over the duration of the beam dwell. The transmitted and received signals are both referred to a stable, and thus coherent, reference signal produced in a local oscillator.

Since a radar target is a complicated reflector or collection of reflectors, the signal-to-noise ratio returned by a target usually varies from pulse to pulse. This variation in target cross section was accounted for in a systematic manner by Swerling[9] in terms of four models summarized in Table II. Scan-to-scan fluctuation (Swerling Models I and III) usually applies to jet aircraft or missiles, whereas pulse-to-pulse fluctuation (Swerling Models II and IV) is representative of propeller-driven aircraft. A point target results in a constant or steady radar cross section and is called a Marcum target model.

The effect target cross section behavior has on the detectability of these various target models is illustrated in Fig. 10. These curves represent the signal-to-noise ratio needed per pulse to achieve a specified detection probability, given a false alarm probability of 10^{-7} and assuming ten successive target returns have been integrated.[10]

Note that for large detection probabilities, a lower signal-to-noise ratio is required to detect steady targets than to detect fluctuating targets. On the other hand, for small detection probabilities, the reverse is true. Fluctuating targets require lower signal-to-noise ratios at small detection probabilities than constant targets, since fluctuating targets will occasionally scintillate in such a manner that a strong target signal will be returned to the radar.

Discriminating targets from clutter: signal processing

In addition to thermal noise, the detection of radar targets is complicated by the presence of clutter. As illustrated in Fig. 11, clutter is radar energy returned by objects in the radar environment other than radar targets. Sources of clutter are stationary objects, land, large bodies of water, and precipitation in the form of rain or snow.

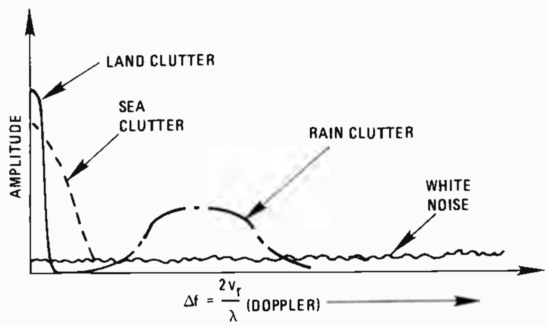

Fig. 12
Clutter can be identified by plotting return amplitude against the doppler frequency. Land is essentially stationary, but moving leaves, branches, etc. produce a spread centered around zero. The sea has more motion associated with it, and so has a wider spread, but is still centered close to zero. Rain, however, is associated with wind velocities, and so has a non-zero mean and a wide distribution.

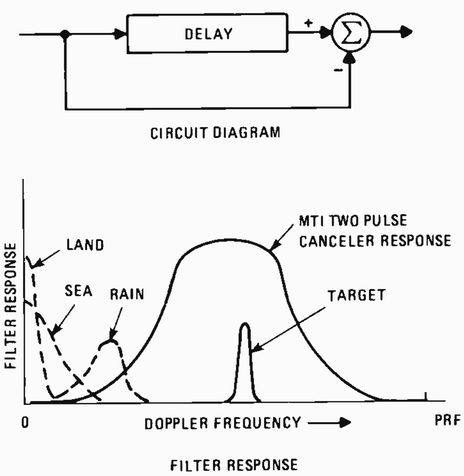

Fig. 13
Moving-target indicator canceler is one method of separating clutter from targets. It works by subtracting successive radar returns from one another and so attenuates signals that have doppler frequencies centered at zero (land and sea clutter) or at multiples of the system pulse-repetition frequency.

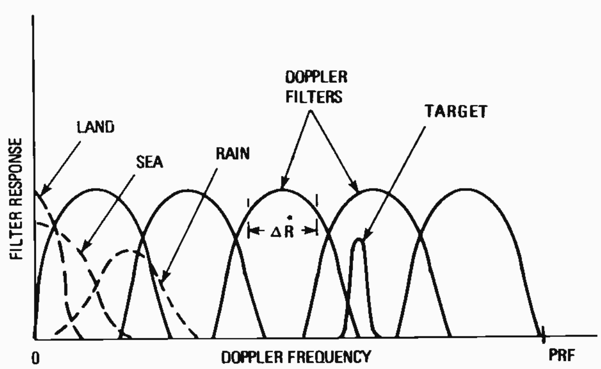

Fig. 14
Doppler filters can be used to separate target returns from clutter in frequency space. Each doppler filter is monitored by CFAR circuitry to differentiate targets from distributed clutter in range.

Unlike noise, clutter exhibits properties that are at least partially correlated from pulse to pulse. Target motion (doppler) can also be used to distinguish a target from clutter.

Land-clutter amplitude is characterized by a reflectivity per unit area. The total energy reflected by land back to the radar depends on the radar pulsewidth, antenna azimuth beamwidth, antenna pointing angle, and the type of terrain. The spectral (i.e., doppler) distribution of land clutter has a zero mean and a small spectral spread. The spread is caused by the rms velocity of the scattering elements such as bushes, tree limbs, and leaves.

Sea-clutter amplitude is similar to land-clutter amplitude in that its reflectivity is specified per unit area. The primary difference between land and sea clutter is the non-zero mean and greater spectral spread of sea clutter. The sea-clutter mean velocity and spectral spread depend on the wind velocity near sea level, water wave height, and water wave velocity.

Rain clutter is a volume effect; its reflectivity is specified per unit volume. The energy reflected by rain back to the radar depends on the radar pulsewidth and the antenna azimuth and elevation beamwidths. Because of high-altitude (up to 20,000 feet) wind shear, rain clutter exhibits a non-zero spectral mean and a large spectral spread.

Fig. 12 illustrates representative land, sea, and rain clutter amplitude as a function of doppler (clutter motion). As is shown, white noise is distributed uniformly over all doppler frequencies.

Targets can be separated from clutter with a Moving Target Indicator (MTI) canceler or a doppler filter bank.

As illustrated in Fig. 13, an MTI canceler subtracts successive radar returns from one another. This results in the synthesis of a doppler filter which, as shown in the figure, attenuates receiver signals that have doppler frequencies centered at zero or at multiples of the system pulse repetition frequency (PRF). Targets that have non-zero doppler will be detected at the signal processor output, whereas most clutter will be suppressed.

Another method of differentiating targets from clutter is to synthesize a doppler filter bank, shown in Fig. 14. This can be done by taking a fourier transform of a train of radar pulses or synthesizing a series of doppler filters from a train of radar pulses. Filter synthesis can take place in either the signal-processing subsystem hardware or in the data-processor subsystem software.

The output of each filter is monitored by CFAR (constant false-alarm rate) logic. The CFAR logic detects threshold crossings that occur over only a few adjacent range cells. This differentiates targets from clutter and suppresses clutter that is distributed in range.

The doppler resolution of a doppler filter bank is determined by the width of the individual doppler filters. Therefore, the filter width is inversely proportional to the effective time the radar illuminates the target.

Radar antenna theory

Most radar antennas are of two general types: reflector or array.

A reflector produces a radar beamshape from a continuous distribution of energy across the antenna aperture. Its optical analog is an aperture, which, when illuminated, results in a diffraction pattern. An array antenna consists of a discrete distribution of radiators across an aperture. Its optical analog would be a one- or two-dimensional diffraction grating.

A radar aperture can be sized and illuminated to produce different beamshapes.

A fan beam is narrow in one dimension and broad in the orthogonal direction. This type of beam can be shaped to concentrate radar energy near the radar horizon and gradually decrease the energy transmitted at higher elevations. Elliptical beams are two-dimensional beams that have an elliptical cross section. Pencil beams exhibit a circular cross section and are used to simultaneously determine target azimuth and elevation.

As mentioned earlier, antenna beam steering is accomplished either mechanically or electronically. A mechanical scan entails moving the pedestal that supports the antenna reflector. Electronic steering can be performed by varying the relative phase of adjacent radiators (either in the feed mechanism or on the face of the antenna). Some radars use a mixture of these two steering methods in which, for instance, the radar beam is steered mechanically in azimuth and electronically in elevation.

Fig. 15 illustrates the parameters that characterize antenna performance. The antenna aperture is the active area of the antenna surface. The power gain of the antenna is determined by the physical area of the antenna, the efficiency with which this area is illuminated, and the transmission wavelength. The half-power beamwidth of the antenna (in radians) is approximately equal to the ratio of transmission wavelength to the aperture dimension. Uniform illumination of the aperture shown would result in a beam that is narrow in azimuth and broad in elevation.

If the aperture shown in Fig. 15 is uniformly illuminated, the far-field antenna pattern in each coordinate would be a $(\sin x / x)^2$ power distribution consisting of a mainlobe and a series of sidelobes. The 3-dB beamwidth would be λ/a and λ/b in the horizontal and vertical coordinates, respectively. The first sidelobe amplitude would be 13 dB below the mainlobe, as shown in Fig. 16.

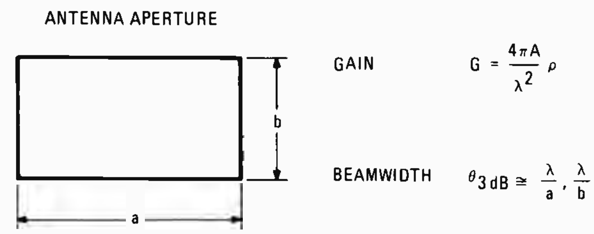

Fig. 15
Antenna parameters depend on surface area, physical dimensions, transmission wavelength, and antenna efficiency.

From a radar standpoint, these sidelobes are high. They could result in increased clutter entering the system through the antenna sidelobes and could also result in large-angle errors if the antenna sidelobes illuminate large targets.

The microwave antenna designer can control sidelobes by varying the illumination distribution across the antenna aperture.

Taylor[11,12] has shown that illumination of an antenna aperture with a series of functions that approximate Chebyshev polynomials decreases the antenna sidelobe level markedly—typical sidelobe levels of 30 dB below the mainlobe can be obtained. As shown in Fig. 17, these lower sidelobes are accompanied by a slight broadening of the antenna mainlobe with a slight loss in angular resolution. The antenna gain decreases

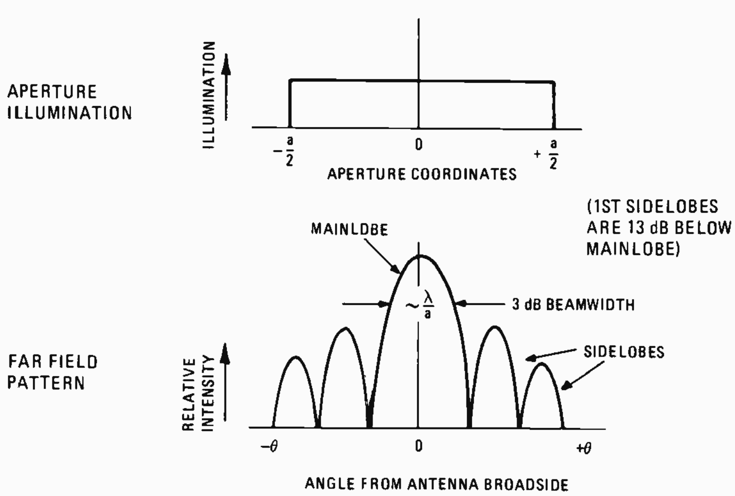

Fig. 16
Antenna pattern for uniform illumination produces a mainlobe and a series of sidelobes. Even though the sidelobes are 13 dB below the main lobe, they are undesirable. Fig. 17 shows one method of decreasing sidelobe amplitude.

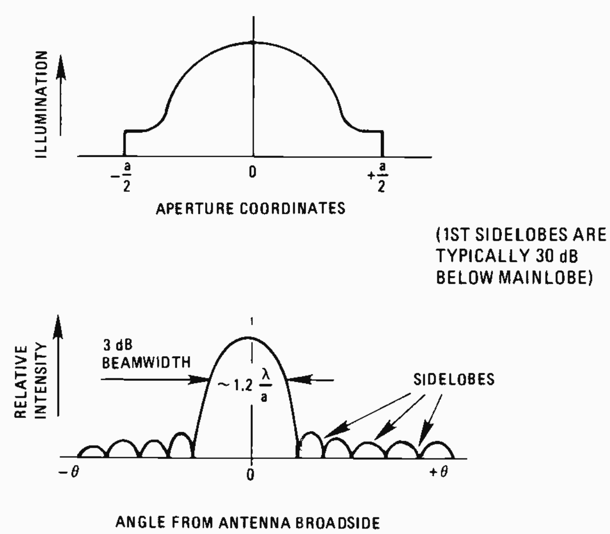

Fig. 17
Sidelobes are reduced by weighting the illumination across the antenna aperture. This weighting is accompanied by a slight broading of the main lobe and a subsequent decrease in antenna gain.

because of the decrease in the antenna illumination efficiency as compared to uniform aperture illumination (i.e., the antenna efficiency factor decreases). Taylor weightings are but one of a number of types of aperture illumination that have been used in radar design over the past thirty years.

Conclusions

Radars measure target echo characteristics (delay, amplitude, phase, etc.) to determine such parameters as target:

1) range;
2) range rate (doppler);
3) angle;
4) velocity (derived from a time history of range and angle measurements); and
5) signature (amplitude time history).

The probability of target detection and the accuracy of target range, range-rate, and angle determination depend on the signal-to-noise ratio returned by the target to the radar. Therefore, a matched-filter receiver is used to maximize the system signal-to-noise rate at the receiver output.

Since radar targets can be obscured by land, sea, and rain clutter, target doppler information is used to discriminate targets of interest from environmental clutter. This is accomplished through the use of MTI cancelers or doppler filter banks.

Radar antenna patterns are similar to the patterns developed by far-field optical diffraction theory. The sidelobes that a radar antenna produces can be controlled and reduced through proper aperture illumination weighting.

A thorough treatment of such an extensive subject as radar is difficult in such a short paper. It is hoped that this general discussion has set the stage for the informative papers that follow. For those interested in a deeper understanding of radar and detection theory, a short bibliography of significant books and papers devoted to radar is given below.

Acknowledgments

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a system/technology perspective—

Radar weapon system sensors

A.S. Robinson

Radar weapon system sensors have evolved from relatively simple electromechanically scanned search radars to multifunction electronic scanning designs that simultaneously search, discriminate, and track multiple targets and weapons in real time—all in an intense and growing radar countermeasures environment.

Early radar technology

Radar sensors have played a critical role in both offensive and defensive weapon systems since they first matured under fire during World War II. Driven by a pressing need for early warning of air attack and for effective deployment of their interceptor aircraft, British scientists and engineers, in a very short period of time, performed the prodigious feat of converting prewar laboratory research in electromagnetic propagation into a successful wartime operational air defense system. It is interesting to review the architecture of this system, and of the environment in which it operated, since it established the basic framework from which modern radar systems have grown.

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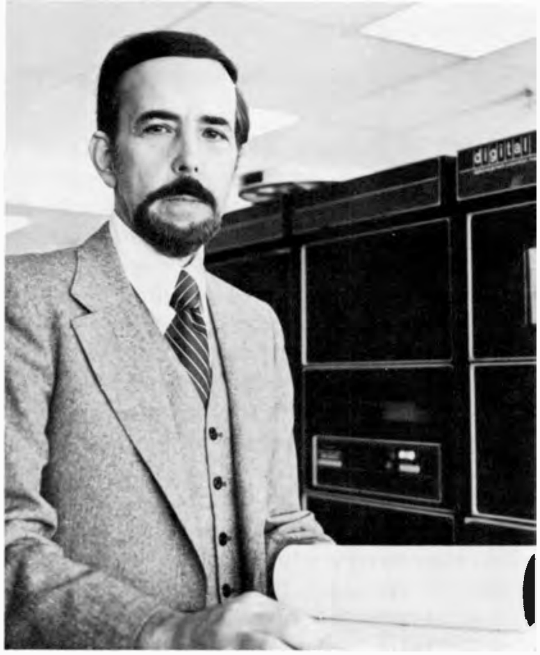


Several tactical factors, matched with radar's abilities, contributed to radar's early success.

First, the threat to be detected consisted of the buildup of large numbers of aircraft into attack formations, and was a time-consuming process, involving sequential takeoffs and climbing to loitering altitudes that were well within the field of view of defensive radars. Second, the radar-reflecting cross sections of individual aircraft were large, so that single aircraft could be detected, and the approximate sizes of assembling forces could be approximated from their net cross sections and distributions. Finally, once turned toward their targets, these formations were limited to the speed of their slowest aircraft, while the speed and climbing capabilities of defensive interceptors, the distribution of their airfields, and the speed of communication from the distributed radar network to centralized operations control, and then on to the interceptors themselves, was fast enough to make it possible to achieve initial interceptions well before target areas were reached.

From a technology perspective, communication equipment developments had already established a technology base for transmitters, receivers, and antennas which, while at lower than optimum frequencies for radar, could be used directly in radar designs of limited angular resolution that were nonetheless effective for their primary "trip-wire" function. This "trip-wire" mode was needed to conserve limited defensive interception resources, making it possible to initiate interceptions only when they were required, with centralized control of tactical reserves, and the ability to match the number of interceptor aircraft to the estimated number of attackers. Once interceptors were airborne, relative, rather than absolute, positions were of importance. Radar tracks of both offensive and defensive formations made it possible for ground controllers to vector interceptors into advantageous attack positions to local control by the interceptors based on visual (and, later, airborne radar) contact.

Initially, radar's critical role in air defense was a well kept secret.

Radar's outstanding success during the Battle of Britain resulted both from this fortuitous matching between air-defense needs and the performance that even early radar technology could provide, and from a lack of appreciation by the offense of the capabilities of these new sensors and of the degree to which they had been integrated into an overall defensive weapon system. As a result, attacks on both radars and command centers were limited, and while significant levels of initial damage were achieved, these attacks were not pursued, so that both radars and interceptor command links remained effective throughout the war. This was the first and last time that a radar-based defensive weapon system was in such a fortunate tactical position. Thereafter, all military commands have understood the major role that radar sensors play, and so have reflected this understanding in the design of both their offensive and defensive systems.

The basic scanning radar designs developed during World War II were based primarily on mechanical scanning.

They included *"2-D" search radars*—antennas rotating in azimuth, using "fan beam" patterns—narrow in azimuth and broad in elevation; *height-finding radars*—antennas slewable to a commanded azimuth position, with antenna patterns narrow in elevation and broad in azimuth so that they could be mechanically scanned in elevation ("nodded") to provide height data; and *tracking radars*—antennas with patterns narrow in both elevation and azimuth, forming a "pencil beam" that could track a target by nutating in a narrow circle around it ("conical scan").

Emergence of electronic scanning

Since these early pioneering developments, mechanically scanning, single-function radars have evolved through several generations of technology improvements and represent, today, the majority of deployed operational radars. Electronic scanning technology has matured during this same time period and is being used increasingly either to augment mechanical scanning or to completely replace it. High-precision, high-data-rate, single-target tracking radars continue to use mechanical scanning in both azimuth and elevation, but conical scanning of the pencil beam about the target has been largely replaced by "monopulse" designs. This approach is based on clusters of feeds that form multiple antenna beams, slightly skewed off the precision antenna pointing axis. (See the paper by Profera.) These beams are processed and subtracted to provide three signals—one proportional to target amplitude that is used to measure range, one proportional to elevation angular deviation, and the other proportional to azimuth angular deviation from the antenna pointing axis. The range measurement and the antenna pointing angle, corrected by the two deviation signals, provide a precise measurement of target position, obtainable during a single radar pulse transmission.

Search radars have evolved to "3-D" designs, with antenna beams narrowed in elevation as well as azimuth. These beams scan electronically in elevation as the antenna rotates mechanically in azimuth. For many applications this represents an effective approach. It provides hemispheric coverage with a single rotating antenna, detects all targets in the radar field of view, and, by processing the series of returns received from these targets as the beam scans past them ("track while scan"), obtains target positions in three dimensions on each rotation (range, azimuth, and elevation angle).

For applications such as unjammed air traffic control, the quality of the resultant target tracks is adequate to maintain required levels of air-space control. For many other applications, however, the data rate and beam-pointing flexibility obtainable with this approach is either marginal or inadequate. The problem arises from the lack of flexibility in the mechanical azimuth scanning technique. As the antenna sweeps by a target or groups of targets, the number of data samples obtained may not be adequate for target discrimination, particularly if the target is immersed in clutter or jamming. The number of returns obtained from a given target on each revolution can be increased by decreasing antenna rotation rate, but such a decrease increases the delay before a new set of samples is obtained on the next revolution. When targets are maneuvering rapidly, the quality of track data deteriorates rapidly between data samples, and is unsatisfactory for many applications. The expansion of electronic scanning in 3-D radars from elevation scanning alone to combined electronic scanning in elevation and azimuth greatly increases radar flexibility and is a clear trend for future 3-D radars. There are, however, many applications such as multiple-target discrimination combined with the control of interception weaponry, in which both search and continuous, precision, high-data-rate, track data is required. In these multi-function systems, a multiplicity of fixed antennas, in which all scanning is electronic, is necessary. This situation first arose after World War II, when ballistic intercontinental missiles were developed and deployed.

The first reaction to this ballistic-missile threat was to develop and deploy a radar network capable of providing early warning of a ballistic missile attack. This network, based on mechanical searching and tracking radar designs, was intended to provide early warning to both military retaliatory forces and to the civilian community. While relatively conventional radar technology was adequate for providing early warning, it proved to be totally inadequate for the problem of providing an active defense against ballistic missiles.

Active defense systems

Multifunction radar capabilities are necessary for active ballistic-missile defense.

The large number of missiles involved, the masses of accompanying decoys and jammers, and the reflecting wakes formed by the reentry of these bodies into the atmosphere combined to create a vast swarm of targets, immersed in noise and clutter, and to impose a new dimension on the radar performance required in search, discrimination, tracking, and fire control. The key problems were and are discrimination and fire control—searching through the target swarm using sophisticated waveforms and signal processing to separate out targets of potential interest, then tracking and performing further discrimination tests on each of these targets at a high data rate to provide precision inputs for fire-control computations. Conventional electromechanically scanned tracking radars can achieve the required data rates only by using one radar for each target, an approach that is not economically feasible for the large number of simultaneous target tracks involved. In response to this threat, phased-array radars

technology perspective 1

Phased-array antennas

Phased-array antenna principles are illustrated in Figs. 1 through 3. The antenna in Fig. 1 rotates mechanically in azimuth, while scanning electronically in elevation. The antenna face is divided into horizontal segments, with rf energy from the radar transmitter distributed to each row through individual phase shifters. The energy from each phase shifter is then distributed to all of the radiating elements in its row. When the phase shifters all receive identical settings, energy emanating from each row adds in phase only along the antenna axis, and a pencil beam is generated in a direction perpendicular to the antenna face. In all other directions, the energy adds with different phases and therefore tends to cancel, with the lack of perfect cancellation leading to antenna sidelobes. As in all antenna designs, the amount of energy lost to these sidelobes can be controlled by tapering the level of rf energy across the antenna aperture.

At the cost of a substantial increase in the number of phase shifters (e.g., to 4900 instead of 70), the antenna beam can be designed to scan electronically in both azimuth and elevation, as illustrated in Fig. 2. The rf energy from the transmitter now reaches each radiating element through an individual phase shifter. By introducing appropriate variations in phase in both the vertical and horizontal directions, the antenna beam can be scanned electronically, typically over angles of ±60°. Typical phase shifters use either magnetic materials or diodes in the rf path, with these devices, in turn, actuated by digital control registers. While the antenna is receiving returns from its last transmission, digital commands are distributed to buffer registers associated with each control register so that, at the end of the listening interval, a single command can transfer the contents of all buffer registers to all control registers, thereby immediately switching the antenna beam to its new pointing direction. A photograph of one face of modern four-face Navy phased array radar—the AN/SPY-1A—is shown in Fig. 3. The AN/SPY-1A phased-array antenna is comprised of approximately 4500 waveguide radiating elements and ferrite phase shifters, and is capable of electronically positioning its narrow beam anywhere within an octant of a sphere.

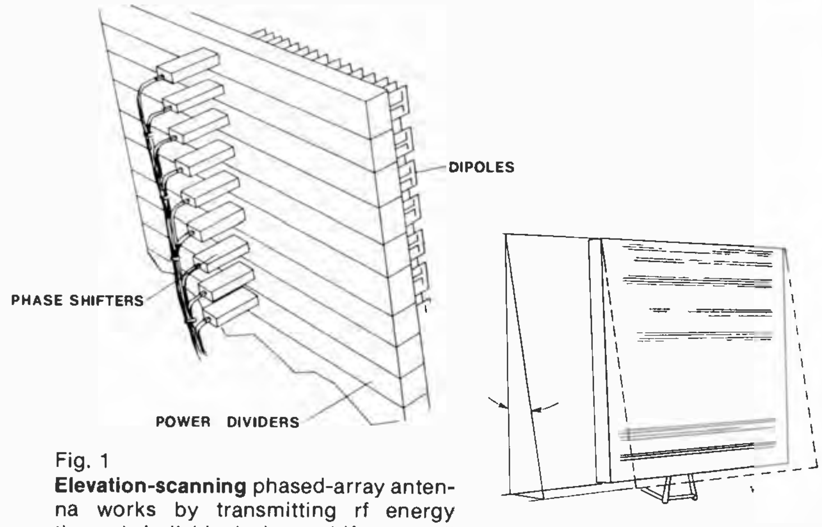


Fig. 1
Elevation-scanning phased-array antenna works by transmitting rf energy through individual phase shifters to all the radiating elements in a row.

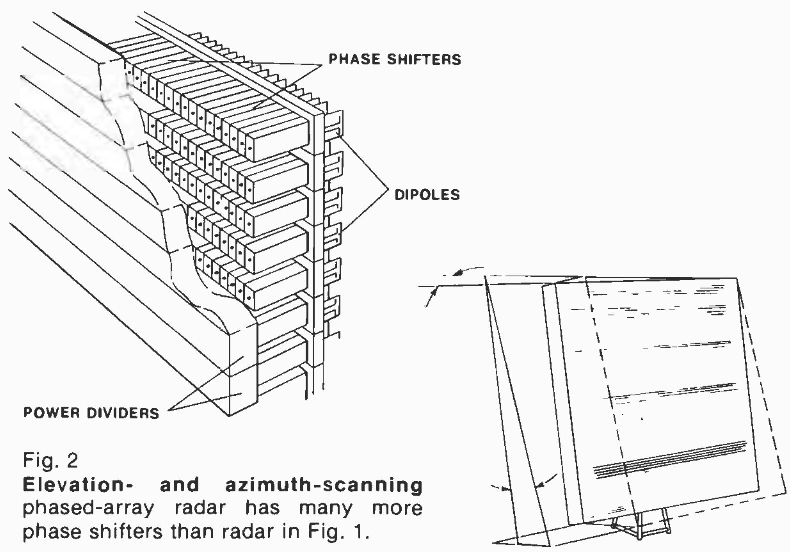


Fig. 2
Elevation- and azimuth-scanning phased-array radar has many more phase shifters than radar in Fig. 1.

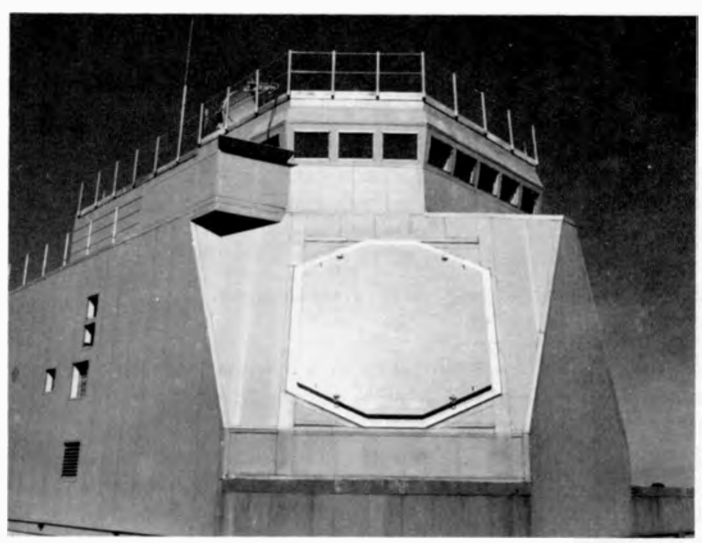


Fig. 3
Modern phased-array radar, the AN/SPY-1A, is used in air-defense system on Navy ships, four antenna faces per ship. This face is on the developmental site at Missile and Surface Radar, Moorestown.

began to come of age. While initial designs were large and expensive, they provided the first radar systems in which the pointing direction of antennas could be changed in a few millionths of a second, thereby making it possible to multiplex search, discrimination, tracking, and guidance functions at high speed. (See *technology perspective 1.*)

Under the impetus of ballistic-missile defense, phased-array radar concepts evolved over the years into increasingly effective hardware designs in a number of frequency bands. Simultaneously, major advances were made in the level of sophistication of radar waveform generation and associated signal processing, in the generation and distribution of high levels of coherent rf energy, and in both the hardware and software required for massive real-time digital data processing. These major radar advances were coordinated with the development of quick-reaction, high-speed interceptor missiles and their associated command, control, and guidance. (The paper by Liston and Sparks shows how radar engineers simulate these sysems as an aid to the design and checkout processes.) The net result of all of these efforts was the establishment of a technology base for ballistic-missile defense that would make possible deployment of a defensive system which, against a full-scale nuclear attack, would have a high probability of intercepting and destroying a significant number of offensive weapons, but a low probability of intercepting them all.

ABM defense deployment has arguments pro and con.

It is possible to reason that deploying such a system would reduce the probable level of attack damage. Alternatively, it can be argued that deploying a strong ABM defense would trigger the production and deployment of a more-than-offsetting number of offensive missiles and so increase the probable level of damage. Starting from these positions, more and more complex arguments for and against ABM defense have evolved. At present, ballistic-missile defense has halted short of full-scale deployment, with substantial ongoing funding directed toward probing the potential impact of new technologies that might upset the present state of nuclear offensive dominance. If current efforts fail to limit the number of nations with both nuclear weapons and the capability to deliver them, it is not unreasonable to envision the eventual deployment of some form of ballistic-missile defense as protection against the relatively small-scale (but highly damaging) attack that such nations will be able to mount.

Radar sensors must be designed as part of an overall system design process.

Lessons learned in attempting to solve the problems of ballistic missile defense are being translated rapidly into the design of offensive and defensive weapons systems for non-nuclear warfare. In the non-nuclear domain, offensive and defensive systems are continuously growing in capabilities in a state of "restless imbalance." The speed and maneuverability of both offensive and defensive weapons is steadily increasing, as is the sophistication of the sensing, guidance, and warhead options that they carry. World War II "time on target" tactics of multiple weapon firing, so timed that all weapons reach the target together, continue in this new weapon environment, so that defensive weapon systems have to be designed to cope with the simultaneous arrival of a large number of targets. Further, the time available between target detection and required weapon commitment has steadily decreased, to the point that time delays inherent in human intervention have had to be minimized and in some situations eliminated. *These and related factors have made it essential that effective weapon systems be designed as total entities, including the platform that carries them, the radar and electro-optical sensors that are their "eyes," the signal and data processing, command and control, and weapon guidance that are their "brains," and the weaponry that is their "striking arm."* The periodic exercising of elements of these systems in actual combat has taught system designers a number of important lessons, not the least of which is the central role to be played by systems countermeasures.

Growing importance of countermeasures

Offensive and defensive weapons system designers seek to design sensors that can see approaching weapons platforms (aircraft, ships, tanks, etc.), and the weapons that they launch (missiles, shells, etc.), determine their locations, velocities and accelerations, and assist in the guidance of weaponry against them. They also attempt to design into their systems techniques to blind, confuse, and destroy the sensors that will probably be deployed against them, and to overcome attempts to blind, confuse, and destroy their own sensors.

In essence, countermeasures has become the name of the game.

The crucial role of sensors—both radar and electro-optical—in modern warfare is now fully recognized, and any and all means for countering their effectiveness is receiving a high level of priority. A substantial percentage of the military intelligence efforts of all nations is directed toward evaluating the capabilities and limitations of opposition weapons and of the sensor/computing techniques that will be used to aim, launch, and guide them. Dual efforts tend to flow from these evaluations—the development and testing of tactics to take advantage of projected performance limitations in opposition systems, and the development of new and/or modernized countermeasure technologies and equipments to further enhance these tactics. Typical anti-radar techniques include low-altitude, terrain-masked attack trajectories; high-power noise jammers to radiate energy matched to radar transmissions, thereby masking intermediate- and long-range target returns; repeater jammers to receive radar interrogations and repeat back a multiplicity of false target returns; decoys designed to simulate high-threat targets in order to induce heavy weapon expenditures from limited weapon inventories; passive reflector dispensers capable of sowing masses of high radar cross section material over large areas, thereby generating large numbers of false targets and clutter; and Anti-Radiation Missiles (ARMs) to receive, home on, and destroy the radar itself, often requiring only radar sidelobe emanations to carry out their mission.

Technology implications

As these new tactics and equipments evolve, their degrees of effectiveness become known through the military intelligence process, and technologies, equipments, and tactics are further modified to counter them.

The impact of all of these factors on radar technology has been profound. One result has been increasing use of phased-array radars, with one radar taking on a number of functions, (e.g., search and multiple-target track), which in earlier systems required the time-consuming sequential use of a number of sensors. Radar bandwidths are being broadened and bandwidth diversity features, such as changing transmission frequency from pulse to pulse throughout this band, will be used to make the task of jammers and deception repeaters more difficult. Where feasible, individual radars will be designed to operate in multiple frequency bands, and within a given battle area, a multiplicity of radars, operating in concert, each in a different part of the frequency spectrum, will be used to improve the probability of discriminating true target from false, of defeating jamming, and of detecting missiles homing on the radiation of a given radar in time to turn that radar off before it is destroyed. Substantial efforts will be expended on reducing radar sidelobes, in order to reduce the signal levels received from radar jammers, as well as easing the task of designing deception transmitters as decoys for the ARMs designed to home on radar sidelobe energy. (See the paper by Scudder.) In general, the line between radar and electronic countermeasure subsystems can be expected to blend and possibly disappear as these subsystems unite in their common task of sensing incoming targets, overcoming jamming and deception, and jamming and confusing sensors deployed against them.

The computation speeds already required by weapons-systems phased-array radars far exceed the wildest blue-sky thinking of the World War II era.

Radars are now required to search volumes that may be hundreds of miles in diameter with resolutions in the order of tens of feet, and to discriminate and track large numbers of targets with still higher resolutions. Limitations in the peak power available with realistic transmitter designs make it necessary to code transmitter waveforms so that pulses of relatively long duration can be reduced by signal processing to the resolution dimension required by the system. (See the paper by Weinstock.) Rain, noise, fixed and movable clutter, chaff, noise jamming, repeater deception jamming, deception targets, and real targets all give rise to radar detections that have to be processed in real time in order to provide the discrimination and targeting information on which the entire system depends.

Pipeline processing, distributed data processing, and low-cost digital LSI make the high-speed computation possible.

Directly following the antenna, required computation rates are often so high that they can only be achieved by "pipeline" computing architectures (see *technology perspective* 2), in which signals are passed through a series of computing elements in a "pipeline" configuration, with all elements operating simultaneously at high speed to achieve the required overall signal-processing throughput rates. Typically, this part of the signal processing retains a limited, but important, level of programmability in terms of such factors as pipeline configuration control, weighting values to be applied to the signals, etc. (See the paper by Timken and Herold.) Typical competing implementation approaches in this area include high-speed digital LSI, surface acoustic wave (SAW) devices, and sampled analog charge-coupled device (CCD) processing. Only after initial detection processing do signal rates usually drop sufficiently to make the use of general-purpose digital data processing feasible. Digital data processing itself is going through an important era of transition. The use of large, high-speed machines with highly complex software, once the only practical design approach due to digital device costs, is giving way to distributed data-processing architectures, (see *technology perspective 3*) now made economically feasible by the advent of low-cost digital LSI devices (*technology perspective 4*). A strong drive is developing to use the opportunity presented by this new architectural flexibility to improve the entire process of system software design, development and test—an area that has proved to be a major cost and performance stumbling block in many recent system developments. The expectation is that substantial simplifications will result from distributing software with hardware in separately testable entities of limited program complexity, while retaining centralized "housekeeping" control of this array of processors, and of data-base functions that need to be shared between them. (See the paper by Buch, Clapper, and Smith.)

Two additional "drivers" underlie present trends in radar technology—one a matter of national style and policy, the second an economic overlay constraining all of the technologically possible alternatives.

Years ago U.S. scientists and engineers used to view the efforts of their U.S.S.R. counterparts with condescension. Each system designed by the Soviets has usually represented a relatively small incremental progression from the prior system designed for that function. The fact that each of these systems has usually been produced in quantity, and distributed to both their armed forces and their allies in a timely manner, wasn't considered in our thinking. U.S. programs have been characterized by use of the highest level of technology currently available, or soon to be available. Resulting systems have been substantially more sophisticated than their U.S.S.R. counterparts. However, these systems have taken longer and longer to develop and have been deployed in limited quantities over relatively long periods of time. The pattern now emerging is that U.S.S.R. systems, having gone through substantial improvements and upgradings over many years, now represent very significant levels of performance and are widely deployed. U.S. systems continue to demonstrate a technological edge, but the margin is simply not as great as before and, in terms of deployed systems, we are clearly behind in many situations.

Hand in hand with this problem is the issue of economic constraints. Our high-technology military systems are increasing in cost at a rate of approximately 400% per decade. As a nation, we simply cannot afford the substantial increase in defense expenditures and/or the decrease in fielded systems that this cost growth implies. In 1978, approximately $124 billion will be budgeted for defense and approximately 10% of these resources will be devoted to research, development, test, and evaluation. It is probable that in terms of constant dollars, the budget segment allocated to the design, development, and production of weapons systems will remain essentially constant. The clear challenge in the years ahead, in every area of defense, will be to identify the essential characteristics required of our weapons systems, and to then focus our technologies on *reducing the cost* of these systems, so that they can be deployed in the quantities required to establish a real defense in being, rather than a defensive potential. All signs point to the probability that, exclusive of guerrilla warfare, when non-nuclear wars occur, they will be of relatively short duration and will involve very substantial attrition. It is unlikely that there will be time to tool up, produce, and deploy systems that are still in research and development at the outbreak of hostilities.

Each of the papers presented in this issue addresses some aspect of this technology/cost balance problem, and the means for driving toward deployed technological excellence at a price that we can afford.

technology perspective 2

High-speed pipeline processing

Directly following the antenna, processes such as matched filtering, convolution, correlation, and spectrum analysis must be performed. Digital implementation of these functions combines the advantages of high performance, stability, noise immunity, and programmability. However, even the largest general-purpose digital computers cannot achieve the processing speeds required for real-time signal-processing applications.

Pipeline processing permits the designer to achieve the desired data throughput at the expense of signal time delay. As illustrated in Fig. 1, signals are passed through a series of computing elements, with all elements operating simultaneously at high speed, to achieve the overall throughput rates required.

Pipeline architectures simplify the control and data storage problems which would occur if the throughput were to be achieved by paralleling large numbers of processors. Furthermore, the Fast Fourier Transform, an algorithm which greatly reduces the number of computations associated with convolution, spectrum analysis, etc., can be easily configured to fit pipeline architecture.

Fig. 2 presents the block diagram of a high-speed digital pipeline pulse compressor developed under Air Force sponsorship using silicon-on-sapphire LSI technology. This processor performs 60 multiplications and 78 additions every 0.1 microseconds, for an effective computing speed of 600,000,000 multiplications plus 780,000,000 additions per second!

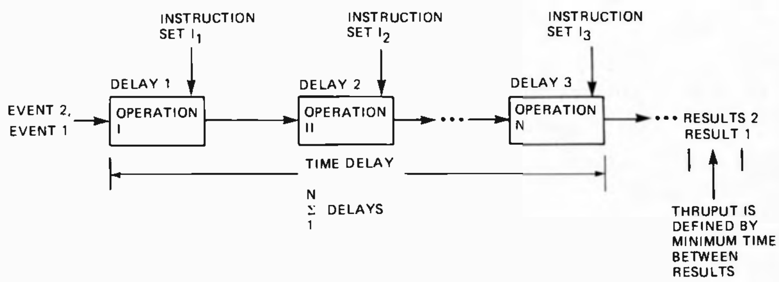


Fig. 1
Pipeline processing achieves high data throughput at the expense of time delay.

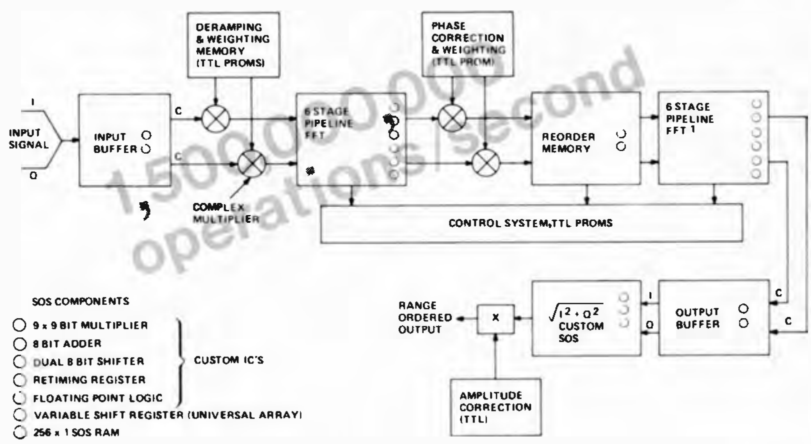
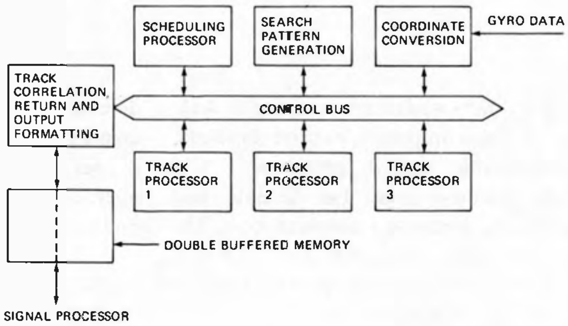


Fig. 2
High-speed pipeline processor performs 60 multiplications and 78 additions every 100 ns.

technology perspective 3

Distributed processing with microcomputers

The block diagram at the right illustrates one architectural approach to the design of a distributed microcomputer system for multifunction radar control. The control processor acts as a control distributor for radar data. Radar return data from the signal processor is correlated with track files residing in the memories of the distributed microcomputers. This is accomplished by the central microcomputer via direct memory access to the distributed microcomputer memories. After correlating old and new data, the control microcomputer provides new data to the appropriate microcomputers, and assigns any new tracks to one or more of the distributed microcomputers, with each microcomputer executing its tracking algorithms independently. Other functions such as scheduling, coordinate conversion and search-pattern generation are also updated concurrently. Depending on the particular radar design, all data-processing functions can be distributed in this manner, or the distributed microcomputers can be used to decrease the processing load of a centralized data processor.



In this approach to distributed microcomputing, the control processor acts as a control distributor for radar data.

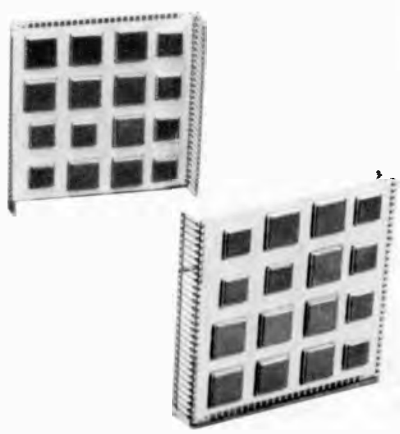
technology perspective 4

High-density electronic packaging

The increased speed and complexity of radar signal and data processing has been matched by major advances in digital logic circuits and packaging.

Following World War II, the invention of transistors provided active logic elements requiring two orders of magnitude less volume than tubes. Logic circuitry shrunk even more in size as numbers of interconnected transistors were placed on the same chip by a process known then as integration—today as small-scale integration. Over the years, we have passed through the development of medium-scale and large-scale integration and are now entering the era of very-large-scale integration (VLSI), with 10,000 to 100,000 active elements interconnected on a single chip—a further increase in packing density of 4-5 orders of magnitude.

The photograph at the right shows a multi-layer thick-film ceramic substrate interconnecting 16 chips on each side of a board that is approximately 3" by 4". Using VLSI technology, this packaging approach will provide circuit densities exceeding 80,000 gates per square inch.



Mirror photograph of thick-film substrate interconnecting 16 chips on each side of the board. VLSI packaging densities will exceed 80,000 gates per square inch.

Radar processing architectures

W.W. Weinstock

System requirements determine the processing structure; flexibility and cost drive the mechanization.

Contemporary radar systems use a wide range of minicomputers, microcomputers, programmable signal processors, and special purpose logic for flexible and reliable operations at reasonable cost. The radar system requirements actually determine which processing architecture to use for a given application.

This paper examines a relatively simple radar system that uses a wide range of typical processing functions. This example illustrates the types of processing requirements that must be handled in modern radars and provides the basis for evaluating the various architectural alternatives available.

A generic radar system example

A track-while-scan (TWS) radar is a search radar whose output data is used to develop tracks.* As a system, the TWS radar (Fig. 1) is relatively simple—a continuously rotating search beam gathers target azimuth and range data. Targets are illuminated on each scan, and their detections are used by the system to form target tracks. It is a good example because it uses a wide range of radar-processing operations: search, detection, acquisition, multiple-target tracking.

*Barry Fell describes the track-while-scan radar in his tutorial paper in this issue.

The signal processor extracts the target from noise and clutter.

To detect a target, the system must separate it from a background of noise and clutter. Noise may be due to external interference or the radar receiver itself. Clutter may be due to backscattering from the earth's surface, or from rain or clouds. The primary function of the signal processor is to reject noise and clutter by suitable filtering, so that the target will be detected every time the beam scans by it.

This calls for the examination of every range-azimuth cell where a target can be present. The total number of cells that must be processed is the number of range-azimuth cells viewed in a single scan. For example, a radar scanning 360° with a beamwidth of 1°, a pulse length of 1 μs (about 500 ft in range), and a maximum range of 500,000 ft, will look at 360,000 cells each scan. With a representative scan period of 3.6 seconds, this means that 100,000 cells must be processed each second.

The number of targets that can be seen during a scan depends on the traffic. A typical value for air-search applications is several hundred, or (nominally) one target per thousand cells. Consequently, the rate of information flow drops by three orders of magnitude after targets are extracted by threshold detection. For radars with better range resolution (say 0.1 μs pulse length, or 50 ft in range) the number of range cells can increase by an order of magnitude but the reduction in the rate of information flow can be four orders of magnitude or greater.

In summary then, the signal processor performs high speed filtering operations, repeated on a range-cell-by-range-cell basis, to extract the signal from a background of noise and clutter. This filtering is followed by amplitude detection and thresholding. To have real-time operation, the processing time must not exceed the time extent of the signal return. For the cases just cited, this is between 0.1 and 1 μs. As we shall see, an extensive sequence of operations may have to be performed during this very brief period.

The data processor correlates the signal processor outputs.

The signal processor *output* is an irregular flow of target-like returns. These can include occasional noise spikes and residual clutter in addition to the targets. The *data processor* now must correlate these returns on a scan-to-scan basis to develop target tracks.

This correlation process must do several things. First, it must associate successive returns from the same target under a variety of conditions. There must be no confusion because of target maneuver or the presence of other returns nearby. The identity of targets on crossing or merging flight paths must be retained. Clutter or interference in the vicinity of the flight path must not be confused with target return data.

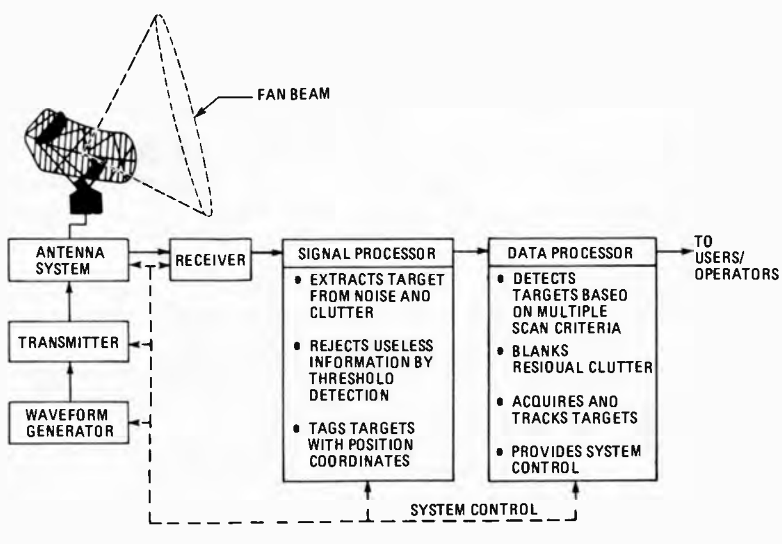


Fig. 1
Generic two-dimensional track-while-scan radar provides a point of departure for considering typical requirements of signal and data processing.

In additon to maintaining tracks, the system must be capable of recognizing a new target; i.e. one which is not currently under track. It must be able to do this without being confused by transient interference or environmental returns. Noise and clutter must also be excluded as soon as possible to lighten the processing load.

Different correlation methods are required to reject noise and clutter. Since noise is random, it will not correlate in position on a scan-to-scan basis. Consequently, some form of multiple-scan correlation process must be used to establish the presence of a new target. Clutter, on the other hand, is strongly correlated scan-to-scan. This fact can be used to map and blank out the residues of strong returns.

In addition to performing its target-handling functions, the data processor serves as the focal point for controlling the system and for disseminating target data. Using its target files, the processor drives operator displays and provides digital data for any higher level system processing required.

Radar system designers today can choose from a variety of processing approaches.

Many current radars employ primarily analog signal processing, while others digitize all processing functions after the the receiver (i.e., after baseband conversion). Although the two approaches exist side-by-side today, this paper addresses only digital implementations since these offer advantages in processing capacity and flexibility—clearly making them favored candidates for the radar system application.

Signal processing functions

The series of operations required to extract a target from a background of noise and clutter is shown in Fig. 2.

All of the returns reflected from the target during a single scan are used in making the detection decision. For the case of the radar with a 1° beamwidth, a 3.6 second scan period, and range of 80 nmi (i.e., 1 ms between pulses), about ten returns are received from a single target during the scan period. Numbers like a few dozen returns are typical. Processing starts on a single pulse with matched filtering. Subsequent operations involve multiple pulse returns.

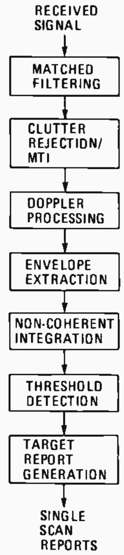


Fig. 2
Signal processing operations involved in extracting target information from a background of clutter and noise.

Extracting a signal from noise is a two-step process that makes use of the differences in spectra.

White noise has a flat spectrum, while the signal spectrum is dominated by that of the single pulse. The multiple-pulse (target) spectrum has a fine structure of narrow lines separated by the pulse-repetition frequency. The specific nature of these lines depends on the time that the target is illuminated by the radar beam and by the target's behavior during that time. For maximum signal-to-noise ratio, we need a filter whose transfer characteristic is matched to the target spectrum.

This matching can be achieved by cascading two filters—a single pulse-matched filter followed by a bank of narrowband (doppler processing) filters to coherently integrate a number of successive pulses from the target. The bandwidth of these filters is a measure of the coherent integration time. In cases where radar instabilities or target fluctuations produce decorrelating effects, it may not be advantageous to coherently integrate all the returns from one pass. In this case, the doppler processing integrates as many as feasible and non-coherent integration (using amplitude information only) completes the job.

Clutter rejection also takes place in two steps.

Since the received signal frequency shifts with target motion, the processor rejects targets whose frequency shift (doppler) is small—signifying small radial velocities typical of clutter. This process, called moving target indication (or MTI), is accomplished by comparing the phase change between successive returns. In practice, this usually involves from two to four successive samples.

The rejection characteristic of an MTI filter is limited by the number of pulses employed. In general, clutter may have some frequency-shift components due either to internal fluctuations (such as those caused by wind blowing the leaves of trees) or to radar instabilities. MTI will not reject these components completely. However, the doppler processing employed for coherent integration has a narrow bandpass which provides the second step of clutter rejection.

Non-linear operations eliminate unneeded phase and amplitude information.

The four filtering operations that were just discussed—matched filtering, MTI, doppler processing, and non-coherent integration—account for the bulk of the signal-processing burden and all involve linear filters. Two non-linear operations are present as well; they destroy information. Envelope detection discards phase information at the point where it is no longer useful. Threshold detection discards low amplitude targets.

The final step in signal processing is the consolidation of all the data into single-scan reports. This requires an estimate of target range and azimuth, and possibly amplitude as well. Such estimates involve computing weighted averages, and this computation is similar to that involved in linear filtering. Following parameter estimation, the data is formatted as needed for the data processing to follow.

In summary then, signal processing involves a sequence of linear filtering and non-linear operations, performed on every range cell of interest. These operations are basically arithmetic—multiplication, addition, and time delay. The computations are summarized in the appendix.

Data processing functions

Data processing involves operations on the signal processor output—a succession of single-scan reports of target position and amplitude. The purpose is to establish target tracks and to reject any remaining

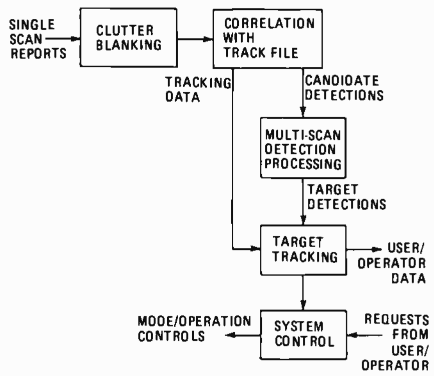


Fig. 3
Data processing involves operations on a succession of single scan reports from the signal processor to provide complete target track information.

undesirable returns. Fig. 3 shows the multiple-scan processing needed for detection, acquisition, tracking, noise and clutter rejection, and system control processes.

The processing burden caused by undesired returns is minimized if these signals are rejected early in the processing sequence.

Clutter blanking removes those residual clutter reports that were strong enough to pass the detection threshold—even after MTI and doppler processing. This makes use of a radar generated "map" of the environment. The map is, in effect, a file of stationary targets that appear on a repetitive basis. Correlation with the map rejects returns in regions where strong clutter will mask desired targets.

Rejection of noise, on the other hand, is based on its *non-repetitive* character. Noise reports are unlikely to correlate geometrically on a scan-to-scan basis. Accordingly, the data processor requires a series of single-scan reports before declaring a detection, thereby rejecting noise before the acquisition and tracking processes are started.

Target data are developed from several single-scan reports.

The only targets that are candidates for detection are those not currently in any active file. Consequently, all single-scan reports must be correlated with the system track file. A target that fails to correlate with an active track is a candidate for the multiple-scan detection processing.

After a succession of reports has been received on a new target, the system can establish velocity information that is good enough to localize the likely position on the next scan. This predicted position is then used as the standard against which the new scan data are correlated. The uncertainty in this position is a function of the quality of previous observations and deviations due to possible target maneuvers. The design of the tracking and prediction filter then becomes a compromise between the narrow bandwidth required for good noise rejection and the wide bandwidth needed to minimize lag errors in the presence of a target maneuver.

The uncertainty in predicted target position for the next scan is the basis for correlation problems in a multiple-target environment. Flight paths can cross; merging or splitting formations can be encountered; targets can fly near strong clutter regions. Each case can produce a problem of maintaining track continuity, and the problem is aggravated by the possibility of a target maneuver at any time.

In addition to track maintenance, the tracking function must also discontinue tracks that show a run of poor quality data or no data at all. If no returns have been received for the memory span of the track filter, then there is no basis for coasting and the track should be dropped. Failure to drop poor tracks will lead to unnecessary processing burdens and correlation problems.

The system control problem is one of changing waveforms and exercising options to match changes in the environment.

The false reporting rate, in particular, must be monitored and controlled so that spurious single-scan reports do not saturate the system. Sector adjustments of threshold levels and blanking may be required to control this situation.

The data processing functions center on the use and management of target files.

The key files hold the information on targets under track, the clutter map, and the list of candidate new detections. The file processing operations involve a series of correlations or data associations in order to make the basic decisions:

- Is the return clutter?
- Is it from a target already under track?
- Is it from a new detection which has not yet passed the multiple-scan detection criterion?

The number of possible branches in this logic is in marked contrast to the signal processing problem involving a fixed sequence of operations on every cell. The sequence of data processing operations on a single-scan report depends on the type of report. A fairly elaborate logic is required to ensure that all the possibilities are considered.

Another major difference between data processing and signal processing is in the degree of regularity of input data.

The data processor receives an input for every threshold detection by the signal processor. The time between reports depends on the geographic distribution of targets and the antenna scan period. In general, the inputs will be irregularly spaced in time. Concentrations of targets can produce peak rates considerably above the average. The signal processor, on the other hand, processes one resolution cell after the other, on a regular basis.

How it's done—implementing the processing functions

The basic processing requirements we have discussed are summarized in Table I. The enormous differences in processing load and speed requirements, as well as in complexity of operations, clearly demonstrate the need for diversity in system development.

The evolving data processing technology has given rise to distributed processing systems whose architectures are tailored to the problem at hand.

Data processing requirements are typical of those imposed on general-purpose computers. In the 1950s and 1960s, data processor designs were based primarily on centralized, large-scale machines. This approach, of course, has been altered significantly with the advent of the minicomputer and the microcomputer, which are based on different technologies.

The impetus toward the use of smaller machines has come from a second direction as well—software development. Small machines mean distributed processing with dedicated software. Monolithic software developments are giving way to modular sets, offering a promise of easing the problems of software management and software change.

The architectural challenge of distributed systems is to partition the problem into

Table I
Comparison of processing requirements demonstrates the need for a wide variety of processing approaches.

Characteristic	*Representative capability required* *Signal processing*	*Data Processing*
Processing load	Millions of inputs/second	Hundreds of inputs/second
Types of processing required	Regular, well defined, arithmetically intense sequence	Variable sequences of logic, control, and arithmetic operations
Processing speeds	Tens of million of operations per second	Hundreds of thousands of of operations per second
Data span	Tens of milliseconds	seconds
Acceptable processing delays	Microseconds	Tens of milliseconds

elements with simple interface and communication requirements. Highly repetitive processing involving a limited number of different operations can be based in dedicated smaller machines. This is why operations such as "smart terminal" drivers and coordinate converters have become distributed elements. The midi/mini/microcomputer hierarchies that are appearing are one aspect of distributed operations.*

However, certain functions by their nature require a strong centralized processing system capability. For example, if a number of processing functions require the use of an extensive set of files, they should share them directly. The alternative to this is duplicating these files for each processor and communicating any changes as they occur. In our generic TWS system, the track files were used in detection, acquisition, and tracking. Since they might contain hundreds of targets whose coordinates are continuously changing, the file users must be tightly tied to the point where the files are generated.

The world of signal processing is evolving from the other direction, with highly structured requirements and extremely high arithmetic content.

The magnitude of the arithmetic processing problem is illustrated by digital matched filtering. A transmitted waveform can be internally coded so that a long pulse can be compressed into a narrow pulse with good range resolution. In this way, high energy can be achieved in a short pulse without exceeding the peak power limitations of the transmitter. Compression ratios of a few hundred to a few thousand are common. If the range resolution is on the order of a hundred feet, then independent cells will be separated by 0.2 μs after compression. This presents a formidable processing burden, as shown in the Appendix.

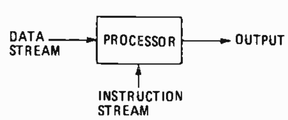
A time-domain form of matched filtering multiplies the received signal by a replica of the transmitted signal and then integrates the result.[2] For the case where the waveform coding has the form of a thousand subpulses, there are 1000 multiplications and additions required every 0.2 μs. This is an unacceptably high processing burden, even for the fastest of current machines. It can be reduced by two orders of magnitude if time-domain filtering is employed using the Fast Fourier Transform and inverse FFT. However, the arithmetic capability required is still very demanding.[3]

Processing requirements drop considerably after matched filtering has been completed. However, the complete sequence (MTI, doppler processing, envelope detection, and thresholding) must be accomplished every 0.2 μs if the processor is to keep up with the input data. Present-day systems commonly require signal processors to achieve 100 times the throughput of a minicomputer with only 10 times the parts count.[4,5] The signal processing implementation problem, then, is one of balancing processing speed and flexibility against cost.

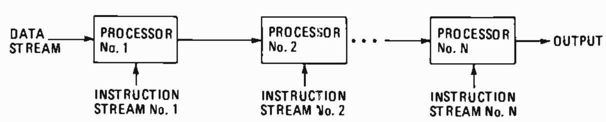
Practical processors typically rely on some form of parallel architecture for high-speed operation.

Processing architectures can be categorized by the number of data streams and the number of instruction streams;[6,7] four typical approaches are shown in Fig. 4. With the exception of the re-entrant processor (Fig. 4a), each type has explicit parallelism in its structure. This parallelism is central to achieving high-speed operation. The array processor (4b) has been used where data is divided on a range basis and different processors perform identical

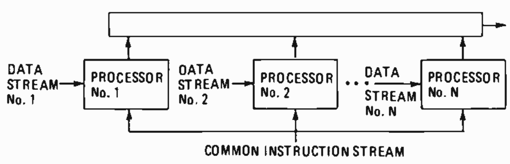
*Buch, Clapper, and Smith discuss distributed processing at the microprocessor level elsewhere in this issue.



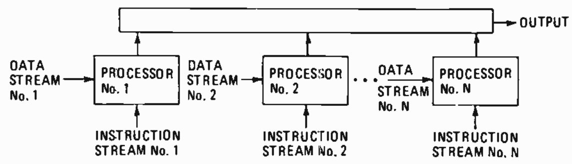
a) **Re-entrant processor**—single data stream/single instruction stream.



c) **Pipeline processor**—single data stream/multiple instruction streams.



b) **Array processor**—multiple data streams/single instruction stream.



d) **Parallel processor/multiprocessor**—multiple data streams/multiple instruction streams.

Fig. 4
Basic processing architectures illustrate differences in approach for handling single and multiple instruction streams.

Table II
Parallelism, in many forms, must be integrated for high throughputs.

Form of parallelism	*Implementation*
Arithmetic	Four multipliers and adders will perform an FFT, butterfly, or second-order section
Memory	Separate instruction and data memories allow parallel instructions and data accesses Two operand memories allow simultaneous fetching of operands for signal processing computations Multiple buses (3) support simultaneous memory accesses
Overlap of instruction and data cycles	Separate logic/control, registers and buses for instruction execution and instruction and data accesses
Parallel control of units which must operate simultaneously	Long instruction word for parallel control Multiple address instructions (3) for data retrieval and storage of results.

processing on cells at different ranges.[8] The pipeline structure (4c) typifies most current hardwired processors. It is also applicable where special microprocessors are used for each processing function, and where the function is established by firmware. That is where processors are converted, for example, into an MTI processor, doppler processor, or non-coherent integrator by virtue of the program used in that element.[9,10] The parallel processor is the most generalized form of parallel configuration.

Parallelism can also be implicit in the internal structure of each processing element. In fact, most high-performance reentrant signal processors are built using the techniques given in Table II. Current signal processing systems use both classes of parallelism. The specific choice for any particular application is a function of the problem and the amount of flexibility desired in the solution.

Flexibility can be achieved in a straightforward manner using digital techniques.

For example, in the case of pulse compression discussed earlier, long codes can be generated by simply adding more subpulses to the waveform. An analog mechanization would require a separate filter for each waveform. Where flexibility is required, the frequently higher cost of digital elements is offset by the multi-mode or multi-function capability of the digital hardware.

Many levels of flexibility are possible. At the lowest level, a hardwired processor may be capable of changing parameters (e.g., bandwidth) without altering its basic configuration. This amounts to changing stored constants within a specific configuration.

On the other hand, the processing system can be implemented using a programmable signal processor, which is a general-purpose re-entrant machine tailored to the signal-processing problem. All of the radar functions can be executed by sequential operations. Changes can be implemented by modifying the machine's program. This approach offers a high degree of flexibility, especially where system requirements are expected to evolve with time. Changes can be accommodated without a hardware redesign.*

But flexibility has its price. General-purpose devices must have capabilities that are not always used in each application. Furthermore, in the case of programmable machines of any kind, efficiency is lost when flexible, high-order languages are employed. The use of machine language yields greater efficiency but makes the software more difficult to change.

A third aspect of flexibility must be considered. This relates to cost as a function of quantity. A common design with wide application is required to obtain a cost advantage. This commonality can be achieved with general-purpose microprocessors as well as with programmable systems. The high-performance microprocessor is well suited to the array and pipeline architectures that were discussed earlier.

* Herold and Timken discuss programmable signal processors in this issue.

Walt Weinstock's early work in extending the area of radar target modeling brought him international recognition through his "Weinstock cases." Later, his leadership in defense system development brought him RCA's highest engineering honor, the 1972 David Sarnoff Award, and recently the IEEE Fellow Award.

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For further reading

Several papers in this issue illustrate a number of specific implementations of the architectures discussed here. They demonstrate some of the state-of-the-art alternatives that RCA is currently investigating. They also show the significance of programmability as applied to signal processing.

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Appendix
Signal processing operations that remove noise and clutter from the radar signal

Signal processing operations are primarily arithmetic in nature, involving a number of multiplications, additions, and time delays.

Linear processing

The linear filtering operations required in signal processing can be examined by considering the filter transfer function

$$H(z) = Y(z)/X(z), \tag{1}$$

where $X(z)$ is the transform of the input signal and $Y(z)$ is the transform of the output. The general transfer function of any system that can be described by linear difference equations with real coefficients (and this covers all the sampled data cases of interest) is of the form

$$H(z) = \frac{Y(z)}{X(z)} = \frac{b_0 + b_1 z^{-1} + \cdots + b_N z^{-N}}{1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_M z^{-M}} \tag{2}$$

The z^{-1} factor is associated with the delay between successive samples; the a's and b's are real coefficients. By cross-multiplying and taking the inverse transform, this becomes

$$\begin{aligned} y(n) &= b_o x(n) + b_1 x(n-1) + \cdots + b_N x(n-M) \\ &\quad -a_1 y(n-1) - a_2 y(n-2) - \cdots - a_M y(n-M). \end{aligned} \tag{3}$$

Thus the current output $y(n)$ is the weighted sum of the present input $x(n)$ and all past inputs to $x(n-M)$, together with past outputs $y(n-1)$ to $y(n-M)$. The general filter is recursive since the output feeds back into the input. This produces an infinite-duration response to any input. For the special case where the denominator of Eq. 2 is a constant, Eq. 3 reduces to a finite-duration impulsive response.

The mechanization of Eq. 3 requires a series of multiplications, additions, and time delays. A wide variety of implementations is available; the choice depends in part on practical considerations—the quantization effects associated with finite word length and the computational efficiency of the candidate architecture.

The computations can be decomposed into a series of simpler computations. Since the denominator in Eq. 2 is a polynomial with real coefficients, its roots are either real or complex conjugates. This means that Eq. 2 can be represented as the product of transfer functions, none of which is greater than second order. Thus, instead of computing Eq. 3 directly, a cascade of second-order operations can be used. This suggests mechanizations which sequentially employ simple second-order sections of the form:

$$y(n) = Ay(n-1) + By(n-2) + Cx(n-2) + Dx(n-1) + x(n). \tag{4}$$

Therefore, the capacity to do four real multiplications and four real additions per step is the basic capability required for time-domain filtering.

Eq. 1 suggests the frequency domain implementation of the linear filter. It requires that $X(z)$, the Fourier transform of the input signal, be computed and multiplied by $H(z)$, the filter transfer function. The inverse transform of the product $H(z)\,X(z)$ then gives the filtered output $y(n)$.

The use of the fast Fourier transform (FFT) algorithm allows the discrete Fourier transform and its inverse to be computed efficiently.[1] The computational burden of the frequency domain approach can be considerably less than the time domain equivalent, even though it involves both a transform and an inverse transform.

The FFT algorithm can be done in steps, by cascading computations of the following type

$$\begin{cases} u(m+1) = u(m) + W^l v(m) \\ v(m+1) = u(m) - W^l v(m) \end{cases} \tag{5}$$

where $u(m)$, $v(m)$ are complex representations of the inputs to the stage; $u(m+1)$, $v(m+1)$ are the outputs; and W^l is a fixed complex multiplication factor. Complex operations are performed by operating on the real and imaginary parts of the quantity of interest. Complex multiplication is equivalent to four real multiplications and two additions. Thus Eq. 5 calls for the same capability needed to do the time domain filtering in Eq. 4. *Therefore, linear filtering requires the capability to do four simultaneous multiplications and additions, regardless of the approach.*

Non-linear processing

The non-linear operations required in signal processing are envelope detection and threshold detection.

Envelope detection removes the phase information from the signal amplitude returns. Prior to envelope detection, the signal is coherent and is represented by two quadrature quantities—an in-phase component, I, and a quadrature component, Q. These are generated by phase detecting the received signals against a reference oscillator and a 90° phase-shifted version of this reference. The components (I,Q) are the elements of the complex signal discussed previously. Amplitude detection requires the computation of $(I^2 + Q^2)^{1/2}$. An exact value of amplitude is not required for the threshold detection that follows. The use of any monotonic function, such as $(I^2 + Q^2)$, will allow for rejection of signals below the critical amplitude level.

Threshold detection involves the simple comparison of the integrated amplitude in a cell with the critical threshold value. If the threshold is exceeded, the return has passed the single-scan detection criterion and is sent on for further processing. If the threshold is not exceeded, the return is irreversibly discarded. Thresholding is the primary branching operation in signal processing.

This brief summary confirms that signal processing operations are primarily arithmetic in nature, involving a number of multiplications, additions, and time delays. Although these operations are relatively straightforward, the number of operations required, in microseconds of time, makes high-speed arithmetic capability an absolute requirement for real-time processing.

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Solid state for super-power radars

The ideal high-speed switch for multi-megawatt pulsed radar modulators may be a thyristor.

D.L. Pruitt

"Dewey" Pruitt joined RCA in 1949, and has been with the RCA Radar Transmitter group at Moorestown since 1953. He has contributed to the design of pulsed radar transmitters for many projects, including particularly the AN/UPS-1, AN/FPT-2, TRADEX, and AN/FPS-95 radar systems. For the past several years, he has been the principal engineer in a series of projects aimed at developing high-power solid-state pulse switches.

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One trend seems inevitable in the continuing radar evolution—a constant demand for more power. In particular, pulsed radar (and laser) systems are already pushing modulator output pulse power levels of several *billion* watts peak—at relatively high (up to 0.5%) duty cycles.* Typical modulator requirements are for pulsewidths of 10 μs, with 2 μs risetime, at 200 to 300 pulses/s. Continuous or intermittent duty may be required, depending on the application.

The heart of any high-power pulse modulator is the pulse-switching device.

Hydrogen-thyratron, spark-gap, and mercury-pool devices—these have been the traditional choices for handling the power levels required. But their size and weight are usually as impressive as their power-handling capacity.

The ideal switch, of course, would be small and lightweight, with long life and high reliability—features that suggest a solid-state approach. This paper describes the five-year history of RCA's investigations of solid-state devices for high-power pulse switching. Several developmental switches are described, with performance ratings that show very real potential as practical switches for high-power pulse modulators.

Background of development

In a line-type pulse modulator, energy is transferred from a high voltage power supply to a "pulse-forming-network" (PFN) capacitance, via a charging inductance and a charging switch. This charge transfer takes place over a relatively long time called the interpulse period. The pulse switch is then triggered to discharge this energy into the load, producing a short, high-peak-power load pulse. The PFN configuration causes the energy to be delivered to the load as a rectangular pulse. After a short interval to allow the pulse switch to recover voltage blocking ability, the charging switch is triggered to initiate another cycle.

Power transistors generally make poor switches in super-power short-pulse modulators, mainly because the peak capability of a power transistor is little higher than its dc capability. This characteristic leads to an inefficient use of silicon, resulting in a large and unreasonably expensive switch. Also, transistors are more susceptible to damage from fault current than are thyristors.

Power thyristors tend to be limited by rms current rather than peak current, and are thus more appropriate for design of a relatively small, low-cost pulse switch. Power thyristors are limited in pulse-current risetime because of slow spread of current across the silicon chip after the gate is triggered. This characteristic (slow rate of current spreading) can cause localized chip overheat for rapidly rising current pulses—the well known *di/dt* limit. Large high-power thyristers are more susceptible. to *di/dt* limitations than are small, low-power thyristors. Several interdigitated and regenerative gate designs have been developed to enhance high frequency performance. However, at the present state of the art, it appears that relatively small chips (up to 0.1 in. diameter and 35 A rms rating) have a definite performance edge over larger devices for pulses with risetimes up to 2 μs.

Device selection

During the early study and investigation, arrangements were made with the RCA Solid State Division to make pulse dissipation tests on several thyristor-device families: RCA S3700M, RCA S2600M, and 2N3899. From these tests, tentative ratings were derived, thus allowing cost and size tradeoffs to be made in order to select the best device for further work. The tests were made using 20-μs pulses, with

*Duty cycle is the ratio of pulsewidth to interpulse period.

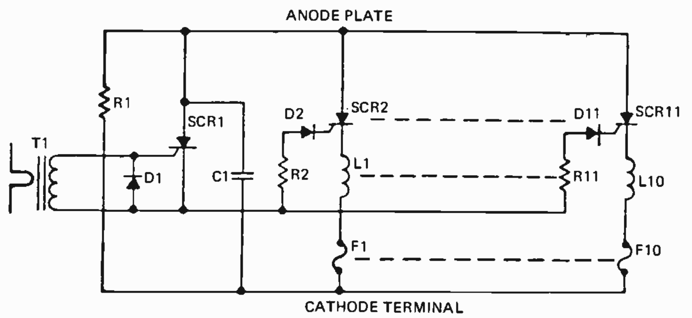

Fig. 1
Basic SCR switch "module" with 10 thyristors paralleled on a common anode plate. (Dotted lines indicate that the SCR circuit is repeated ten times.)

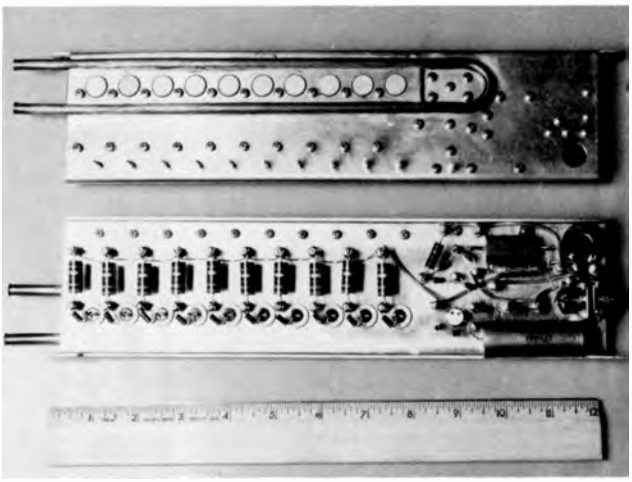

Fig. 2
Parallel SCR switch, showing press-fit thyristors on a water-cooled aluminum plate.

risetime up to 2 μs, and a low repetition rate.

The resulting data showed that one 2N3899 can replace four S3700Ms or three S2600Ms. The significantly higher parts count with the smaller devices seemed certain to make a S3700M or a S2600M modulator more expensive than a 2N3899 modulator. Further, a 2N3899 modulator would be smaller in overall size. Therefore, the 2N3899 (stud mount)/2N3873 (press fit) family was selected for further work.

Developing the switch

The switch was fabricated in two steps:

1) A "module" was constructed by paralleling a number of individual devices on a common anode plate.

2) A number of "modules" were connected in series to obtain the desired voltage capability.

A ten-thyristor module yielded 1.8 megawatts of peak power.

After an evolutionary period of many months, a module using ten type-2N3873 thyristors pressed into a common anode heat sink was developed. (Ten is an arbitrary number; any convenient number up to probably several dozen may be paralleled.) As shown in Fig. 1, a pilot thyristor (SCR1) provides gate drive to the ten main thyristors by switching the voltage on C1 onto the common gate bus. C1 is charged to the module anode-to-cathode voltage. Gate-isolating resistors R2 through R11 ensure a proper overdrive (2 A peak at the nominal 500 V operating level) into each of the main thyristor gates. Diodes D2 through D11 provide further gate isolation, preventing feedback from a leaky or shorted thyristor to the gate bus. Inductors L1 through L10 are straight No. 18 bus wires, each approximately 4 cm long, which connect the ten main cathodes to the next anode plate for a series stack. Fuses F1 through F10 provide automatic disconnect of an individual failed thyristor.

Pilot thyristor SCR1, an RCA S2600M, is normally triggered by a nominal 1-A (peak), 5-μs pulse from current transformer T1. The secondary of T1 has 50 turns of magnet wire on a small (CF111-Q1) ferrite toroid. In a series stack of modules, a 50-A (peak) primary pulse is conducted through a single-turn primary which links all of the toroids in series. The primary turn is a silicon rubber-insulated high-voltage wire.

Early versions of the module were constructed using the stud-mounted 2N3899 thyristors on a water-cooled copper plate. Later versions were constructed using press-fit 2N3873 thyristors on a water-cooled aluminum plate. Fig. 2 shows this latter version.

These switch modules were extensively tested in a conventional artificial line type modulator circuit at 6000 A peak. They yielded 1.8-MW peak power and 9 kW average power.

Using RCA2N3873 thyristors selected at random from a lot of 1000 units containing two different date codes, current sharing among ten paralleled thyristors typically fell within ±20% of the average value. Two continuous runs of 8 hrs each were made at the given conditions. In destructive tests, the devices exhibited remarkable toughness: at least four, and sometimes five of the ten devices had to be removed (by clipping the cathode leads) before failure occurred among the remainder in a 5-minute test. Typically, soft solder melted at the cathode connection before the device failed in these destructive tests.

Twenty modules were connected in series to produce a 30-megawatt switch.

On the basis of the encouraging early results, the Air Force in 1974 awarded RCA a contract to construct and test a 30-megawatt switch.

Twenty modules were constructed, using ten type 2N3873 press-fit thyristors in parallel in each module; the 20 units were connected in series to form a 10-kV peak-voltage, 6-kA peak-current switch (Fig. 3). A modulator was constructed to test this switch to 50 MW peak power and 150 kW average power.

This switch has been operated for short periods (up to 5 minutes) at the full design power levels. (The thermal constant of the thyristor switch is short compared to 5 minutes.) With water cooling provided, the switch heat sink temperature rise was only a few degrees Centigrade. Longer operational periods were precluded by the danger of overheating test set components,

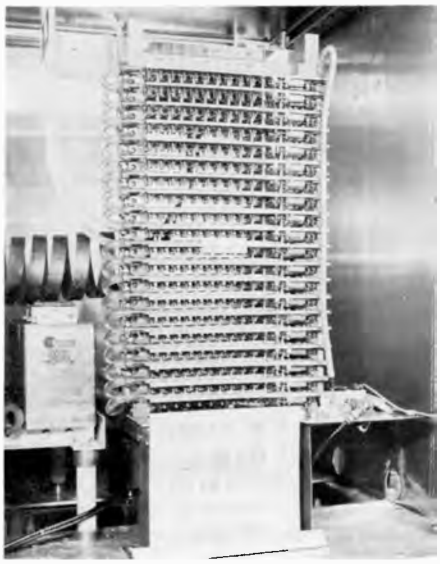

Fig. 3
30-megawatt switch shows 20 modules in breadboard configuration used to verify high-power switching performance.

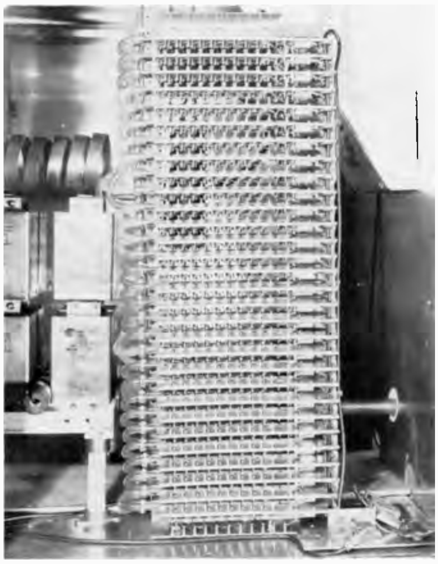

Fig. 4
Extension of switching voltage capability from 10 to 15 kV was demonstrated in this developmental switch.

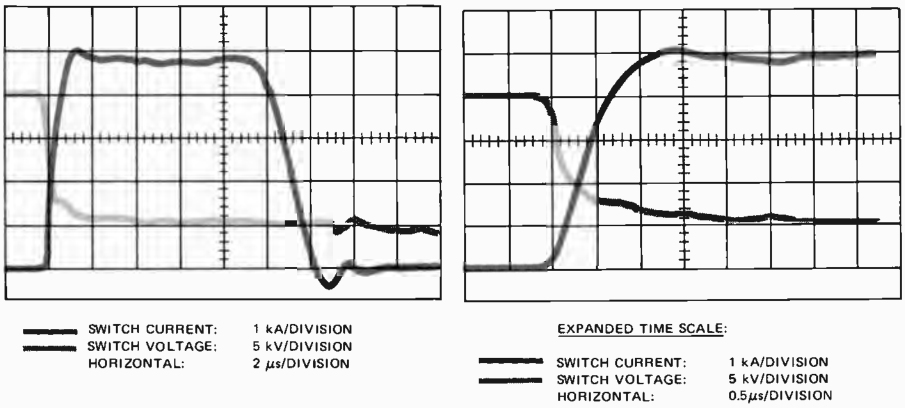

Fig. 5
15-kV switch current and voltage waveforms show instantaneous switching capability on normal 2 microsecond time scale (left) and on an expanded 0.5 microsecond time scale (right).

particularly the pulse-forming-network capacitors.

Levels achieved were:

Peak switch voltage	10 kV
Peak switch current	7000 A
Peak load power	32 MW
Average load power	160 kW
Pulsewidth	20 μs
Current risetime (10% to 90%)	1.7 μs
Repetition rate	250 pulses/s

Adding ten more modules produced an additional 15 megawatts of peak power.

Under a contract extension from the Air Force, the 10-kV, 30-MW switch described above was extended to a 15-kV switch by adding 10 additional modules in series for a total of 30 series modules. (See Fig. 4.)

Because of test-set limitations, this 15-kV switch could not be tested to its full inherent capabilities of 45-MW peak and 225-kW average power. Therefore, the switch was tested for the following parameters:

Pulsewidth	10 μs
Current risetime	0.8 μs
Peak PFN votage	15 kV
Peak load current	4700 A
Peak load power	30.9 MW
Repetition rate	285 pulses/s
Average load power	88.1 kW

The switch was repeatedly snapped on and off at full power, demonstrating instant full power availability without warmup. Continuous runs were again limited to about 5 minutes by component (PFN-capacitor) heating. Fig. 5 shows switch current and voltage waveforms during the pulse.

Hybrid circuit thyristor switch

Early in this program, the use of hybrid circuit techniques was recognized as offering a potential dramatic reduction in size and weight for the parallel SCR switch module. Glass-passivated chips of an appropriate size became available in 1975 (from Unitrode Corporation), and a hybrid circuit development program was started in 1976.

A 40-A (rms rating) 600-V chip (R044060) was chosen; this chip is 5-mm (0.2 in.) square. The concept involves attaching, by reflow soldering, 20 main switch SCR chips in a ten parallel/two series configuration, plus two trigger (or pilot) SCR chips, on a beryllia substrate. Beryllia was chosen for its excellent thermal properties—high conductivity and high specific heat.

The resulting circuit (Fig. 6) is essentially two series circuits, much like the configuration shown in Fig. 1, but with an important simplification. The electrical isolation of the SCR anodes, provided by the beryllia heat sink, allows placement of the fuses (F1 to F20) in the anode circuits; this, in turn, eliminates the requirement for gate-isolating diodes (D2 to D11 in Fig. 1). Otherwise, circuit operation is exactly as described earlier.

Several trial layouts were generated and discarded in arriving at the hybrid circuit layout. Because of the high rms currents involved (40 A rms/chip), the SCR chips are not soldered directly to the substrate metallization, but rather to copper contact pads which are in turn reflow soldered to the metallization pattern. The printed-circuit resistors (gate resistors and bleeder resistors) add negligible weight to the hybrid circuit. The trigger transformers (T1 and T2) and the circuit capacitors (C1 and C2) contribute significant (but not major) weight to the hybrid module.

The completed module weighs 190 grams without cooling fins, and 235 grams with cooling fins attached. Fig. 7 is a photograph of a completed hybrid-circuit thyristor-switch module.

The performance objective, as an air cooled switch, was as follows:

Peak voltage	1 kV
Peak current	3 kA
Pulsewidth	10 μs
Current risetime	1 μs
Repetition rate	100 pulses/s
Duty cycle	0.001
Peak power	1.5 MW
Average power	1.5 kW

Ten hybrid SCR modules were connected in series to obtain a 10 kV (nominal) air-cooled switch as shown in Fig. 8, and the switch was installed in the test modulator. In initial testing, some difficulty was experienced with module voltage sharing, resulting in loss of devices. After repairs, maximum voltage was limited, resulting in the following maximum operation:

Peak voltage	8.9 kV
Peak current	3 kA
Pulsewidth	10 μs
Current risetime	1 μs
Repetition rate	100 pulses/s
Duty cycle	0.001
Load resistance	1.2 Ω
Peak load power	10.8 MW
Average load power	10.8 kW

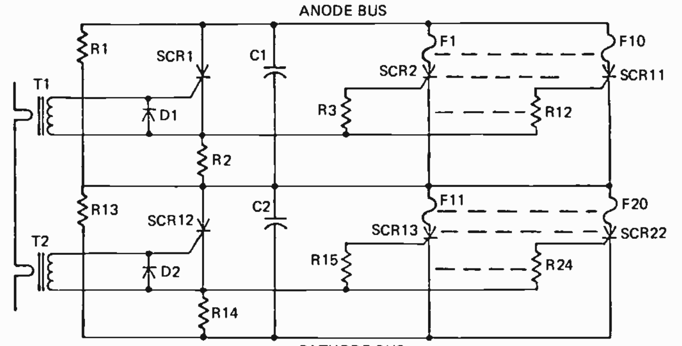

Fig. 6
Hybrid SCR chip switch circuit provides 20 switching chips without the requirement for gate-isolating diodes. (Dotted lines indicate that the SCR circuit is repeated ten times.)

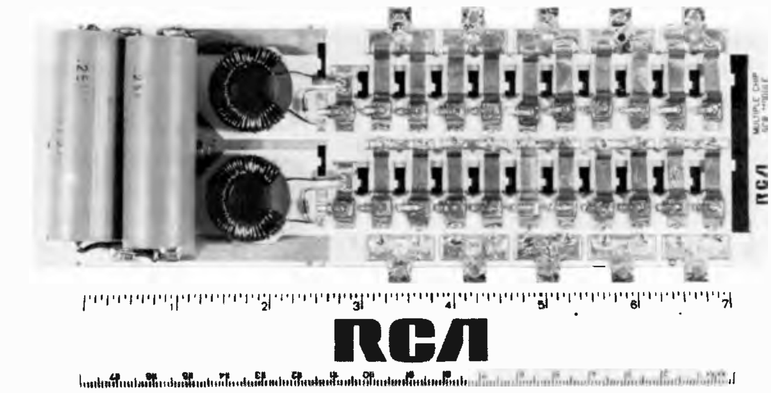

Fig. 7
Hybrid switch module in completed form shows compactness attainable in final design.

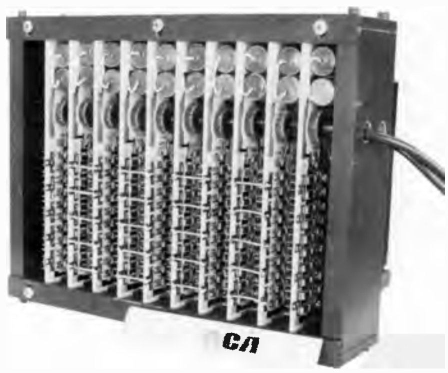

Fig. 8
Air-cooled hybrid switch incorporates ten SCR modules in series for high-voltage testing.

Conclusions

The work performed on thyristor switching has shown that series/parallel arrangements of relatively small thyristors can be used effectively in high-power artificial line-type pulse modulators. A 30-MW (peak) 150-kW (average) power modulator was demonstrated using packaged 2N3873 devices with water cooled heat sinks. A lightweight, compact, air-cooled hybrid SCR switch attained 10 MW peak and 10 kW average in an artificial line-type modulator. These results show that solid-state switching has arrived as a practical reality for advanced super-power pulsed modulator applications.

Acknowledgments

Part of the material contained in this paper was published in the *Record* of 1976 Twelfth Modulator Symposium sponsored by IEEE. Significant portions of this solid-state modulator development work were sponsored by the Air Force Systems Command's Rome Air Development Center, Griffiss AFB, N.Y. The following RCA personnel made significant contributions: E.O. Johnson, RCA Laboratories; E.M. Leyton (deceased) formerly of the RCA Laboratories; and G. Albrecht, formerly of the RCA Solid State Division.

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Pulsed GaAs FET microwave power amplifiers for phased-array radars

R.L. Camisa
J. Goel
H.J. Wolkstein
R.L. Ernst

Phased arrays require pulsed operation at high frequencies, but at the beginning of this project, nothing had been published on the pulse characteristics of GaAs FET amplifiers.

The successful realization of I-band (8-10 GHz) airborne phased-array radars depends upon the development of high-performance economical power-amplifier modules. IMPATT diode amplifiers and transistor amplifier-multiplier approaches have been unsuccessfully tried at these frequencies. At lower frequencies, three-terminal silicon bipolar transistors are used exclusively. Recent advancements in GaAs technology indicate that efficient power amplification is possible, with many researchers[1,2] achieving output power in excess of 1 W through 12 GHz.

This paper summarizes the performance of a 9-10 GHz, 0.5-W pulsed GaAs FET amplifier developed as part of an Air Force exploratory technology program.[3] The amplifier reported here is considered a driver for higher-power stages yet to be developed, with an eventual output power goal of 5 W. In array-radar applications, the amplifiers must be operated in a pulse mode such that the devices are activated only when a radar pulse is being transmitted.

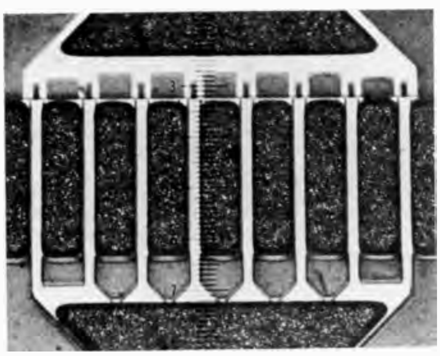

Fig. 1
Typical RCA GaAs FET chip before flip-chip mounting.

At the inception of this program, there was no published prior art concerning the pulse characteristics of GaAs FET amplifiers. Therefore, the major goal of this effort was to compare the cw and pulse performance of microwave amplifiers using these devices. The evaluation of phase variations within a pulse was of particular interest for this phased-array application, since low phase variations make amplifier-to-amplifier tracking problems less difficult.

The distinctive features of RCA GaAs FETs used in this amplifier program are briefly summarized below. Flip-chip bonding procedures, first applied to GaAs power FETs by RCA, presently differentiate our approach from others in the field and will be described. The amplifier design approach discussed here emphasizes pulse techniques and associated tradeoffs.

Device technology

Flip-chip devices have distinct advantages.

The distinctive features of RCA's GaAs FETs used in this amplifier program are: a) flip-chip bonding, for its heatsinking qualities and reduced source inductance; b) self-aligned gate processing, for its simplicity; and c) multiple-layer epitaxy, for its non-degrading ohmic contacts. The details of the device processing have been previously published[1,4] and only the highlights will be briefly reviewed here. Our fabrication processes use conventional photolithographic techniques and avoid difficult alignment problems. Modern microfabrication techniques such as ion beam milling are used, avoiding undercutting and resulting in an almost 1:1 ratio of photoresist pattern to actual device geometry.

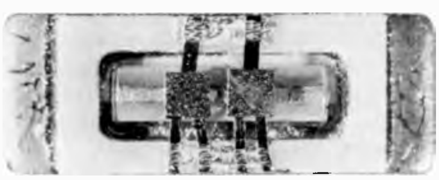

Fig. 2
"Flipped" device mounted on a gold-plated copper carrier. This technique provides good heatsinking and low source inductance.

Flip-chip bonding of devices allows optimal heatsinking of units in a common-source configuration, while at the same time optimizing gain by reducing source inductance to a minimum. This technology uniquely lends itself to high-performance, reliable devices which can ultimately be adapted to large-scale production. Fig. 1 shows a typical RCA GaAs FET chip with plated source posts. Fig. 2 is a photograph of a "flipped" device mounted on a gold-plated copper carrier. In the flip-chip bonding, ribbons or bond wires are attached on gate and drain pads and the device is then flipped down onto a copper carrier, thereby contacting all the sources at the same time. The gate and drain connections are then tacked down on a ceramic ring having metallization pads. Inductance is minimized by grounding all sources directly, without the use of wirebonds. The copper pedestals extract heat directly away from the surface of the device, where the heat is generated. The flip-chip technology appears difficult, but this technique has proved very practical with the advent of commercially-available flip-chip bonding machines.

Amplifier development

The overall multistage amplifier was designed in modular blocks.

This design allowed individual sections to be separately optimized and cascaded easily with other stages. A modular construction is also desirable because it is tractable—if an individual amplifier fails, it can be easily located, reworked, or replaced by an equivalent unit. The most common type of modular design is the quadrature-coupled balanced amplifier.[5] In this construction, each amplifier stage requires two quadrature couplers and two single-ended circuits. The main disadvantage of an all-balanced approach is that two devices per

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Why do we need high-frequency pulsed amplifiers?

Airborne radars are requiring higher and higher resolution, and high-frequency operation (up to 12 GHz) can provide it Higher frequencies also mean smaller antennas and less aircraft weight. However, standard amplifiers do not work well at such high frequencies, and GaAs MESFET amplifiers seem to fill this gap.

It is also efficient to have an airborne radar work in both the air-to-air and ground-to-ground modes. (The driving force here is for military tactical aircraft, but future commercial applications seem possible—collision avoidance with the air and ground are both important.) Thus, the radar must be able to "look" in a number of different directions in a very short time. Phased-array radars do this well, but they pulse beams in different directions by combining a large number of different-phased beams. By varying the individual phases, the combined beams will cancel each other out in different directions, resulting in a beam that can change its direction quite rapidly. The requirement for rapid pulsing is thus passed on to the amplifier.

Ray Camisa was project engineer for the GaAs amplifier described here. His work at the Microwave Technology Center has also included GaAs FET devices and linear amplifiers. He has also published papers on low-noise parametric amplifiers, microwave integrated circuits, and MIS varactors.

Contact him at:
Microwave Technology Center
RCA Laboratories
Princeton, N.J.
Ext. 3136

Jitendra Goel is presently working on GaAs MESFETs and amplifier circuit design. His work has included the first X-band amplifier with an output above 1 W and the first dual-gate high-gain octave-bandwidth (4-8 GHz) amplifier.

Contact him at:
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Ext. 3166

Herb Wolkstein is now concentrating on the development and applications of solid-state microwave devices. He was previously Manager of Advanced Programs and Application Engineering for RCA's microwave activity, where he made many contributions to TWT and solid-state technology.

Contact him at:
Microwave Technology Center
RCA Laboratories
Princeton, N.J.
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Bob Ernst has developed and supervised the construction of hundreds of microwave integrated circuit modules operating at frequencies ranging from 70 MHz to 40 GHz. He is now working on power-combining techniques and the pulsed-microwave system described here.

Contact him at:
Microwave Technology Center
RCA Laboratories
Princeton, N.J.
Ext. 2510

Authors Wolkstein, Goel, Ernst, and Camisa, along with the microwave amplifier described in this article.

amplifier stage are required. An alternate approach uses directly cascaded amplifiers without couplers. The disadvantage of this amplifier type is that individual amplifier stages interact with each other, which makes tuning the complete amplifier difficult. The advantage of the directly cascaded amplifier, however, is that a minimum number of devices are used.

The final version of the driver amplifier used a mixed single-ended and balanced design as a compromise between the number of devices used, alignment difficulty, and overall volume. This was done by separating the amplifier into three distinct modules. The two output modules are balanced stages. The input module is a circulator-coupled, three-stage single-ended amplifier. Fig. 3 is a block diagran of the overall amplifier showing stage-by-stage performance. At band center, the output power of the overall amplifier was 500 mW with an associated gain of 30 dB. The small-signal gain was 33 dB and the noise figure was 12.5 dB.

The amplifier video circuitry design and rf-pulse operation differentiate this amplifier from all previous FET amplifier designs.

In an airborne-array application, in order to conserve power, the FET amplifiers should be off when no rf pulses are being transmitted. Two methods of pulsing the amplifiers were considered: pulsed-gate and pulsed-drain.

In a pulsed-gate configuration, the device is cut off by putting a reference voltage larger than the pinchoff voltage on the device. In order to turn the device on, a positive-going pulse decreases the effective negative gate-to-source voltage such that the FET can draw its normal operating current. In the second approach, the drain voltage is pulsed from 0 V to the normal operating drain potential and current. The drain-biasing scheme requires a fast current driver and the gate-biasing scheme does not. However, a disadvantage of the gate-pulsing scheme is that it puts heavy demands on the maximum voltage that the device must tolerate without damage—the device breakdown voltage must be greater than the algebraic sum of drain voltage, gate voltage, and rf voltages. Our amplifier used the gate-biasing scheme because of its simplicity and ultimate lower cost. Also, the amplifier was pulsed only in the last two balanced stages, where most of the power is being dissipated.

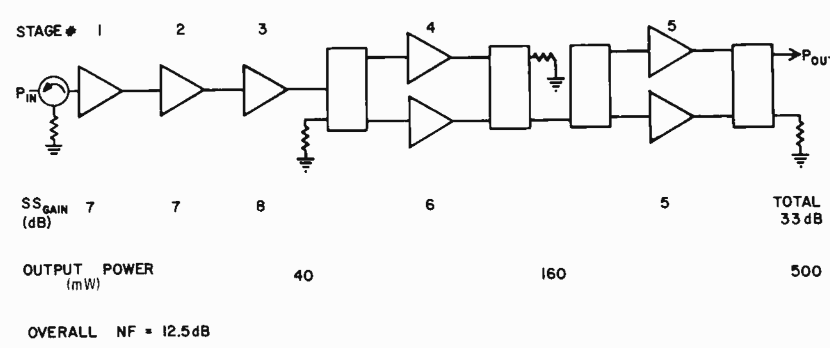

Fig. 3
Stage-by-stage performance of the GaAs FET amplifier. Pulsed operation takes place in the last two stages, where most of the power is dissipated.

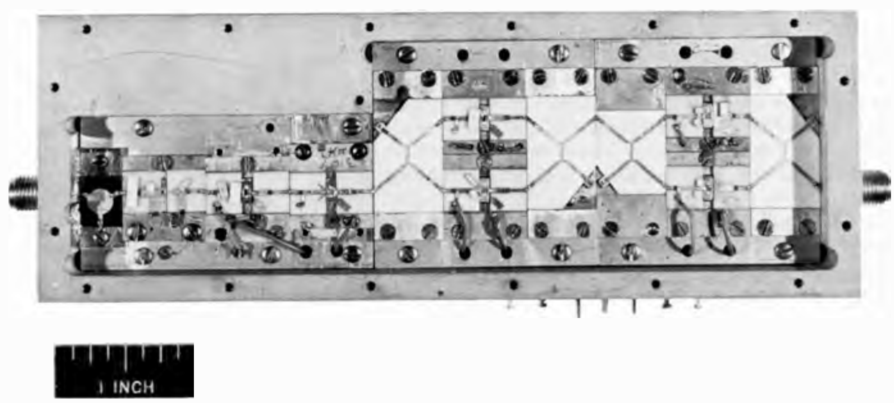

Fig. 4
Experimental amplifier was produced in a microwave integrated circuit format. Note the modular approach taken and compare the modules with the blocks of Fig. 3.

The amplifier performs well, especially in terms of its AM/PM conversion.

Fig. 4 is a top view of the amplifier delivered to the Air Force Avionics Laboratory. The overall package is approximately 15×6×2.9 cm. The input and output connectors are the hermetically sealable type with excellent rf performance through 18 GHz. The amplifier requires two dc inputs ($V_D = 8$ V, $V_{ref} = -4$ V) and one video pulse (0 to −4 V). With −4 V, the last two stages are cut off, and with 0 V, the amplifier is turned on. The amplifier package is divided into rf and dc (or video) compartments.

The amplifier rf circuits were fabricated in a microwave integrated circuit (MIC) format. All circuits were made on 0.635-mm (0.025-in.) Al_2O_3 microstrip transmission lines with chrome-copper-gold metallization. The substrate thickness is dictated mainly by the type of coupler used in the balanced design. Actually, at I-band, a thinner substrate is preferred to minimize dispersion and radiation effects.

Table I summarizes the design goals of the amplifier and the experimental results; Fig. 5 shows the amplifier in pulsed operation. The amplifier met all room-temperature design goals except power-added efficiency. The poor efficiency resulted from having to select devices with high breakdown voltages so that the FETs could be pulsed. This should not be a fundamental problem for the reasons stated in the article's conclusion. The AM/PM (amplitude-modulation/phase-modulation) conversion performance of this amplifier was excellent. At frequencies within the desired band, the AM/PM conversion was so low that it was hardly measurable. With further optimization, AM/PM could be further reduced over the entire band to approximately 2°/dB.

Conclusions

A five-stage GaAs FET amplifier with 29.7 ±0.4 dB gain at 500 mW output power over the 9-10 GHz band was designed, fabricated and tested. Extensive characterization of the amplifier performance was carried out under cw, pulsed-rf, and pulsed-rf pulsed-bias conditions to assess its suitability for airborne phased-array applications. The amplifier performance under cw and pulsed conditions was almost identical. To obtain pulsed amplifier stages not sensitive to the duty cycle, the gate of each FET was pulsed from pinchoff to its operating potential. This technique eliminated the need for fast current drivers, but put stringent constraints on the dc characteristics of the rf devices. If this gate-biasing technique is to be used, all the rf devices must have similar pinchoff values and their breakdown voltages must exceed the algebraic sum of pinchoff voltage, applied drain voltage, and the total rf voltage swing at maximum power output. In the limited time available for developing this amplifier, it was difficult to meet these dc requirements and simultaneously obtain good rf performance. This problem is not a fundamental one, but it underscores the need for further optimization of circuit and/or FET geometries specifically designed for pulsed-rf applications.

Acknowledgments

The authors gratefully acknowledge the support of the Air Force Avionics Laboratory, Wright-Patterson Air Force Base, for their encouragement and support of this work. All power devices used in this program were supplied as part of another X-band power FET program. Dr. H. Huang was the project scientist for the device-development effort. The cooperation of W. Reichert, P. Pelka and J. Klatskin in handling the devices is gratefully acknowledged. All the FET amplifier circuits were assembled and optimized by M. Kunz.

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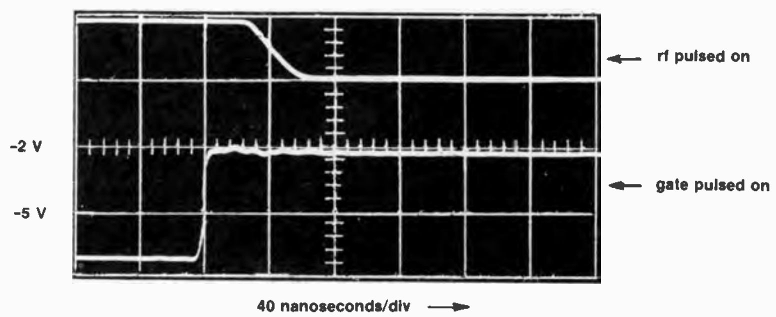
Table I
Amplifier performance met all room-temperature design goals except power-added efficiency. Low efficiency came from having to select devices with high breakdown voltages so that the FETs could be pulsed.

	Design goal	*Experimental results*
Gain and frequency response	30 ± 0.3 dB over 9- to 10-GHz band at 500 mW output power	29.7 ± 0.4 dB at 500 mW output power
Output power	500 mW	500 mW
Efficiency	20%	8%
Pulsewidth Repetition rate	0.2 to 65 μs 300 to 0.3 kHz	Both requirements met
Rise/fall time	50 ns (max)	< 30 ns
AM/PM* conversion	3°/dB (max)	3.5°/dB (max)
Pulse-amplitude droop	5% (max)	⩽ 5%
Intrapulse phase shift	5° (max)	< 5°
Unit-unit gain/ phase tracking	0.6 dB in gain 7° in phase	No data obtained in program time frame

*AM/PM = amplitude-modulation/phase-modulation



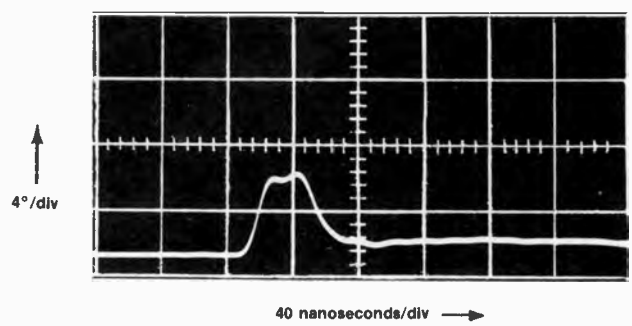


Fig. 5
In pulsed-gate operation (top) a positive-going pulse decreases the effective gate-to-source voltage and so allows the FET to draw its operating current and turn on. Resulting phase imbalance (bottom) is within specifications.

- **RCA Engineer—ranks second (after discussions with associates) as a source of technical information about RCA.**

- **TREND—ranks second (after the grapevine) as a source of non-technical information about RCA.**

- **RCA Libraries—rank fifth as a source of all information—rated right after: Your own files (some of which have been accumulated with the help of the library), the engineers in your own group, books, and handbooks (many provided by the library).**

- **RCA Technical Abstracts—ranks lowest of the four, partly because of its low visibility.**

Engineering Information Survey results Part 3

D.E. Hutchison | J.C. Phillips | F.J. Strobl

A closer look at four information sources—how important are they to you?

What value do RCA engineers place on the *RCA Engineer*? *TREND*? *RCA Technical Abstracts*? The RCA libraries? The recent Engineering Information survey answered these questions and several others* related to these four RCA-sponsored communication channels:

How accessible are they?
How are they used?
What should be done to improve them?

*An earlier paper focused on the general results of the Engineering Information Survey.[1] A second paper compared the information needs and use patterns of high and low achievers.[2] This paper reviews four specific technical information sources available to RCA engineers.

How accessible are they?

Most engineers follow the path of least resistance.

Research on the use of information sources shows that accessibility often determines frequency of use.** Engineers frequently turn first to the information source that is most accessible; perceived technical quality influences his decision to a lesser extent. This implies that improving the quality of an information source may not lead to increased use of that source—unless it is accessible.

**See, for example, Allen, T.; *Managing the flow of technology* (MIT Press; 1977) p. 184.

How accessible is the RCA Engineer? Trend? RCA Technical Abstracts?

	% of respondents having access		
	RCA Engineer	*TREND*	*RCA Technical Abstracts*
Direct access	73%	67%	9%
Indirect access	13%	23%	36%
No access	14%	10%	55%

Direct access means that the information is distributed directly to the engineer's office or home. Sources identified as *indirect access* are available through circulation or borrowing. *No access* means these sources are not available or not used.

RCA Engineer is distributed on a company-paid subscription basis and is generally sent to an engineer's home. According to the Survey, coverage varies substantially by location (100% in some to virtually none in others). Research and development engineers get the most complete coverage; manufacturing and service engineers, the least.

TREND is sent in bulk quantities to each engineering location within RCA. A distributor in the location routes sufficient copies to engineering groups for distribution to each engineer. The survey indicated that about 10% of the respondents did not receive TREND.

RCA Technical Abstracts is distributed to libraries, to engineering management, and to those who feel they have a need for direct access. Many survey respondents (55%) have no access (do not know what *RCA Technical Abstracts* is or have no access to it.)

What is your access to an RCA Library?

Library at my location	77%
Remotely located library	7%
No access	16%

Library services are available to most survey respondents; 77% have direct access and 7% can take advantage of the central library of their major operating unit.

How are they used?—a question of value

How would you rate RCA Engineer, TREND, RCA Technical Abstracts, and the RCA libraries as sources for the following types of information?

	RCA Engineer	*TREND*	*RCA Technical Abstracts*	Library
Tech. info—job related	60%	42%	37%	90%
Tech. info—other	90%	68%	37%	93%
Business info-RCA	70%	95%	N/A	82%
Business info—other	30%	47%	N/A	81%
Professional	61%	56%	N/A	85%

This table summarizes the percent of respondents who said these sources are valuable, very valuable, or somewhat valuable.

Do you use the RCA Engineer, TREND, and Technical Abstracts to find personal contacts with experts with whom you can discuss technical matters?

	RCA Engineer	TREND	*RCA Technical Abstracts*
Source has provided contacts with experts.	39%	28%	18%

Let's analyze what these data tell us about the value of each of these technical information sources.

RCA Engineer:

The above data confirmed:

—that the *RCA Engineer's* major value is as a source for general technical information. (Tech info—other.)
—that it is a valuable source of business information about RCA.
—that in some cases it can be very valuable as a source of job-related information, but
—that it has only moderate value as a source for industry-related business information.
—that another important measure of the *RCA Engineer's* usefulness is its value in fostering intracompany, interdivisional contacts.

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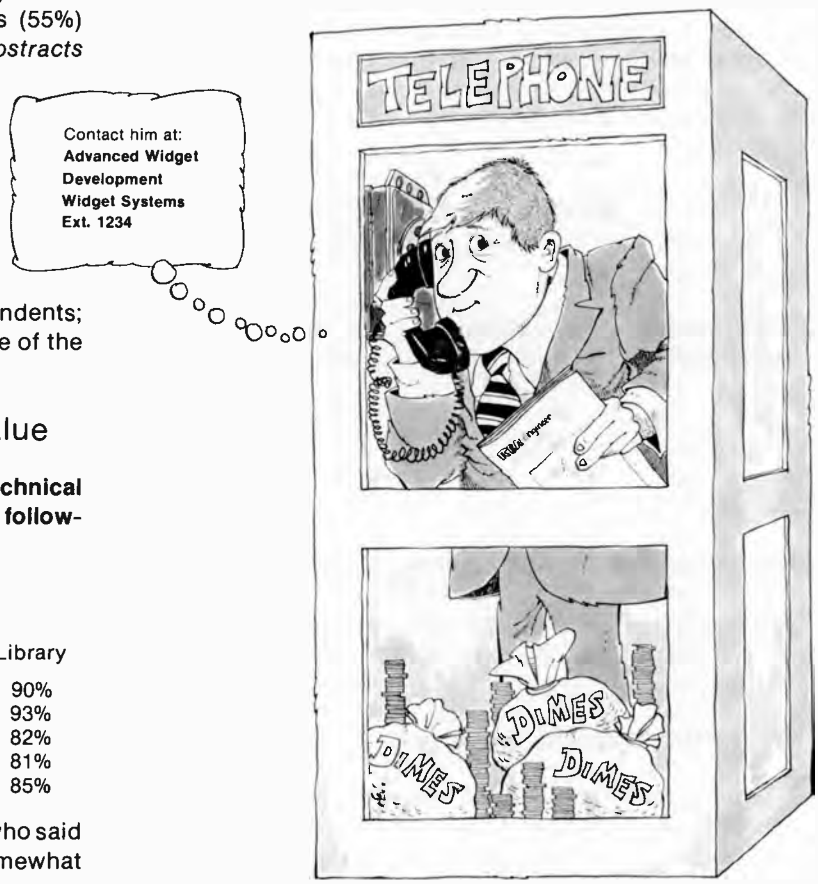

Thirty-nine percent of RCA Engineer readers have used the journal to locate experts on technical matters.

TREND

The **R**esearch and **E**ngineering **N**ews **D**igest, is valued as a primary source for business information about RCA, has fairly high value as a source of general technical information about RCA, and is of moderate value for the remaining three categories of information (professional, business-other, and technical-job related).

RCA Technical Abstracts

Although *Technical Abstracts* is valued by 37% of the respondents, this constitutes the lowest ranking of the four sources considered. One of the reasons for this low ranking is that 55% of the respondents did not have access to *RCA Technical Abstracts*.

Library

The libraries rate very high and maintain an image of providing material in all five areas of information to 81-93% of the respondents. There is little question that their value ranks highest among the sources covered here.

How much of most issues of the RCA Engineer and TREND do you read and scan?

	RCA Engineer	*TREND*
Read	20%	41%
Scan	52%	46%

The *RCA Engineer* publishes over 500 pages a year; thus, each year the average survey respondent reads over 100 pages—a considerable reading volume. An interesting finding was that the percentage read was similar for all types of engineers (research, design, manufacturing) but varied greatly with professional achievement (discussed later).

TREND presents short capsules of diverse items: respondents read what interests them and scan the rest. The almost 50/50 read/scan relationship suggests a good mix of content.

How often do you obtain copies of reports or papers referenced in RCA Technical Abstracts?

	RCA Technical Abstracts
Use more than twice a month	4%
Occasionally	29%
Never use	67%

RCA Technical Abstracts is used by 33% of the survey respondents, 4% at least once a month, and 29% use it occasionally. Recalling that only 45% have access (9% direct, 36% indirect), many of those who have access follow through by obtaining copies of the documents abstracted.

How often do you use the Library?

Libraries accessible at a location are used by 77% of the respondents; 48% use it more than twice a month; 29% occasionally. The heaviest use is for literature searches, followed by reading current journals and proceedings. Other uses of the library range from checking Military Specifications and vendor information to seeing what's new and finding a quiet place to work. 9% are too busy to use the library, and 4% say that their management discourages them from using the library.

How does achievement level relate to access and use of these sources?

An earlier paper on the Engineering Information Survey[2] compared the differences in information use between high and low achievers.* It showed that high achievers use appreciably more initiative in seeking out information and make the effort required to be well informed beyond the immediate job. Generally, the same pattern shows up in the data for the four information sources reported below.

	% of respondents answering positively	
Access	*High achiever*	*Low achiever*
Receive *RCA Engineer* at home	84	46
No access to *RCA Engineer*	5	33
Receive *TREND*	78	56
Direct receipt of *RCA Technical Abstracts*	63	28
Library at my location	86	60
Use (by those who have access)		
% of *RCA Engineer* read	21	16
% of *TREND* read	42	37
Use *RCA Technical Abstracts* twice a month	12	4
Never use *RCA Technical Abstracts*	20	44
Use library more than twice a month	70	45
Never use library	2	13

*Achievement was measured by six criteria: perceived technical currentness, effectiveness as an information source, and the number of papers, presentations, patents, and awards.

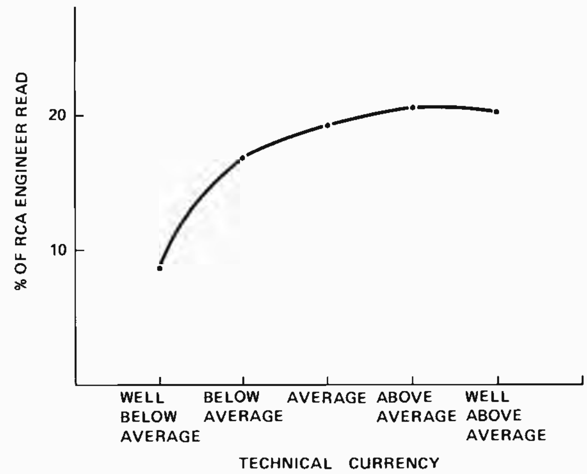

Fig. 1
RCA Engineer is read more by engineers who perceive themselves to be more up to date. Respondents were asked to rate themselves in terms of being up to date with the current state of the art in their technical field; these responses are plotted against percentage of the *RCA Engineer* that is read for each category.

We were able to derive several other interesting relationships from this comparison and other survey analyses:

RCA Engineer

- Engineers who read more of the *RCA Engineer* regard themselves as being more up to date (see Fig. 1).
- Engineers who have more access to the *RCA Engineer* perceive that their management places more emphasis on staying up to date.
- Engineers who have more access to the *RCA Engineer* are used more frequently as technical information sources.
- Engineers with more professional achievements have better access to the *RCA Engineer* and use it more to find personal contacts with whom they can discuss technical matters.

RCA Technical Abstracts

- Those who find *RCA Technical Abstracts* most useful are those who receive it directly.
- Those who regard their management as placing strong emphasis on keeping up to date had easy access to *RCA Technical Abstracts.*
- Those receiving *RCA Technical Abstracts* directly rated themselves near the top in keeping up to date.
- Engineers who have more access to *RCA Technical Abstracts* have more patents, papers, presentations, and awards (Fig. 2).

Library

- Those who put more emphasis on keeping technically current make more use of, and have better access to, libraries.
- Those who use the library more also publish more papers, make more presentations, file more patents, and win more awards (Fig. 3).
- Those who have used computer-assisted searching have more professional accomplishments.

What can we do to improve?

The survey results contained many recommendations for enhancing the value of the information sources covered.

What could make the RCA Engineer more important?

By far, the most common response to this open-ended question was for "more directly job-related material." Other write-in suggestions repeated most often were:

—include more tutorial or self-study material.

—include more state-of-the-art technology.

—make it easier to understand—less math, less technical.

—go into more technical depth.

—make it more applications oriented.

Following up on this open-ended question, the survey attempted to delve more specifically into recommendations for change.

When asked about state-of-the-art reviews, for example, more than 79% of the engineers responding (about 2100) considered it important to publish more of this type of article in the *RCA Engineer.*

Respondents were asked to write-in state-of-the-art topics and other topics that should be in the *Engineer*, along with

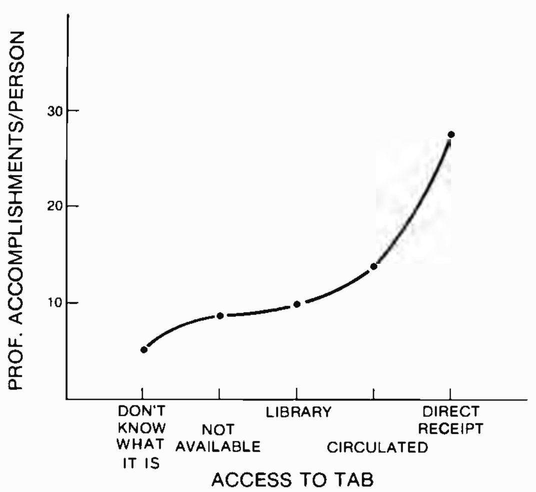

Fig. 2
Access to RCA Technical Abstracts relates to accomplishments (papers, patents, presentations, awards).

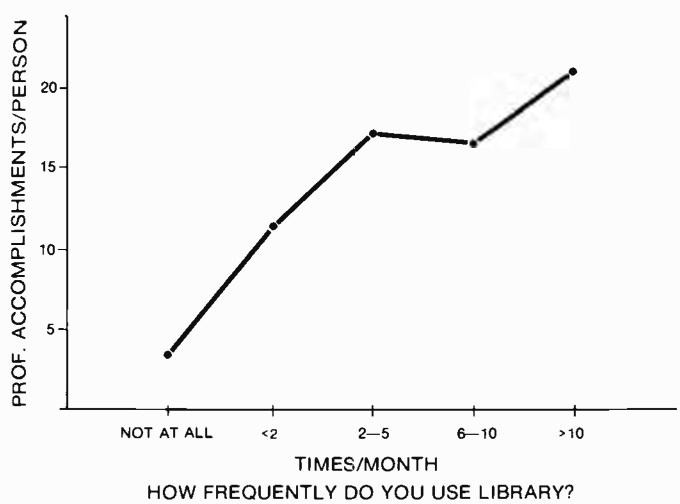

Fig. 3
Library use correlates strongly with professional accomplishments. Engineers who visit their libraries frequently are those who are writing more papers, making more presentations, obtaining more patents, and receiving more awards.

TREND is second only to the grapevine as a source of nontechnical information about RCA.

suggested possible sources or authors. Table I lists the most frequent recommendations by general topic.

Table I
General topics that survey respondents suggested for the *RCA Engineer.* (The list is in order of the popularity of the topics based on write-in answers to the question "What would you suggest as some of the more important topics to be covered in the *RCA Engineer*").

- Computers/digital technology
- Solid state technology and applications
- Manufacturing
- Communications
- Business/policy
- Profiles of other activities
- Electro-optics
- Circuits
- Mechanical engineering and packaging
- Television
- Heat transfer
- Career information
- Devices
- Materials

The survey also provided a listing of types of information that might be useful and asked respondents to check as many as apply. The results are given in Table II.

Table II
More information about competitive technology and more educational presentations were the two strongest survey requests. (These are responses to the statement "The *RCA Engineer* should have more information about.")

	% of respondents answering %
Competitive technology	64
Educational presentations—for self-study	52
Profiles of divisions and activities	40
Various aspects of engineering as a profession	33
Educational presentations—for career guidance	28
Technical reference file (technical bibliographies of various topics compiled by experts)	28
Blue-sky look into the future	27
Entertainment (electronics is fun and educational; hobbies, etc.)	23
Book reviews	20
Two-way communications/letters to editor	13
Profiles of engineers	12
Picture features (photo essays)	12
Interviews	10

What subjects would you like emphasized more in TREND? What are the subjects you would like emphasized less?

The results, in descending order of importance, show the percentage of readers desiring more information in a particular area, minus the percentage of those desiring less emphasis:

New products, developments	65%
New markets	52%
Business	51%
Scientific advances	48%
Policy	35%
Available services (Library, MIS, Information Services, etc.)	24%

What services could the library provide that would be helpful to you that it does not now provide?

In the answer to this question, there seemed to be a general feeling that our libraries are not being kept up to date because of budget limitations. Requests were made for more up-to-date books, broader coverage, more copies of popular books so there wouldn't be such a long wait for them, and a larger selection of journals and conference proceedings.

Library users would also like their libraries to have more space for older material, which now must be discarded. They would like on-line computer searching, audio-visual aids and materials, video tapes of RCA courses, catalogs of holdings in other RCA libraries, bulletins from their library listing new acquisitions, faster response time on documents requested, and better copying facilities.

Reactions to the survey—what are we doing with these results?

RCA Engineer
John Phillips, Editor
Contact him at:
Corporate Engineering, Cherry Hill, N.J.
Ext. PY-4254

As I reported in the August-September issue,[3] we have already started publishing more review and survey articles, more tutorial information, and more about RCA's businesses. We plan to continue these efforts. Further, we feel that most papers we publish—whether product-, technology-, or application-oriented—can teach, can make some mention of the business climate, and can review related developments. To that end, we have been encouraging authors to include additional broader-interest material in each paper. This may be a perspective statement added as a "box" to the article, or it may simply be an expanded introduction, further explanation of the theory, stronger conclusion, or clarifying illustration.

Most important, we are making the needs of our broad readership known to potential authors as we invite papers for future issues; we are also insisting that those needs be met as a condition of publication. Many engineers wanted more information on the competition and on competitive technologies. Here we hit a real obstacle. Including information on competition is difficult, partly because such information is difficult to get, and partly because the *RCA Engineer* is published by RCA. While we cannot evaluate our competitor's products in a company-sponsored journal, we will stress competing technologies in any technology review we publish. For example, in the August-September 1977 issue, the paper on CMOS Reliability, by Larry Gallace, *et al,* also treats bipolar device reliability. In the same issue, Jerry Bouchard and John Bauer reviewed the competing hybrid technologies, not just the ones used at their locations.

Because access and use of the *Engineer* relate so strongly to the survey's measures of engineering achievement, we are continually working with management to broaden the distribution, and have directed much of our editorial resources toward improving readability. Direct distribution to *all* engineers remains a primary objective.

We have also taken steps to build upon the journal's value as a source of personal contacts for technical information. This shows up in several ways:

- Direct statements within the body of each article, letting readers know where more information is available from the author or from others at RCA.
- Useful references and bibliographies.
- Specific contact information for each author.
- Reviews of work being done around the company (e.g., "Where the electro-optics action is at RCA" by Haynes, Apr - May 1977)

We plan, to use the many write-in suggestions for articles and features. As the mechanism for follow-up, all the suggestions from a location will be given to the Editorial Representative for that location. If we obtain half of them, we will fill the pages of the *Engineer* for at least the next decade.

When we come to the question of including material related directly to every engineer's job, we have a real problem. Many of us would like to solve our next major problem by simply picking up a piece of literature. But no information source is that good. And, although the request for directly job-related information was a major recurring theme of this survey, the best we, as information gatherers, can do is make it easier for readers to determine what is relevant to their jobs and provide them efficient tools and methods for further literature or expert searching. We are emphasizing the importance of useful references and bibliographies in each article; and, as reported, if an article has some bearing on a particular job, author contact is simple and straightforward.

In summary, then, the survey results set a major goal for the *RCA Engineer* staff, Editorial Representatives, and authors: to produce a journal that meets the needs of the readership—said another way, to produce a journal "by and

Many readers of RCA Technical Abstracts follow through by obtaining copies of the documents it abstracts.

for the RCA Engineer." This survey was a large step in a continuing process of trying to better understand our readers' needs and interests, recognizing, of course, that these needs and interests change continually. We will continue to solicit your ideas and try to be responsive to your needs.

TREND—The Research and Engineering News Digest
Frank Strobl, Editor
Contact him at:
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Ext. PY-4220

The survey results have provided an additional perspective on what *TREND* readers want to see in RCA's technical news digest.

A main concern that generally underlies all the survey data is how *TREND* can be more useful to RCA engineers. One of *TREND's* purposes is to point out to engineers where useful information can be found—Continuing Engineering Education courses; valuable resource materials (such as RCA Library programs, RCA-MIT Industrial Liaison Symposia); RCA technical symposia; and engineering or marketing contacts who can provide in-depth information on technical work going on in other divisions.

This last item is receiving special emphasis because the Survey indicated that 59% of RCA engineers "never use *TREND* to find personal contacts with whom they can discuss technical matters." To remedy this, a contact name is being included in every story covering a technical achievement.

Business information about RCA fared well in the readers' ratings. *TREND* includes business information not only on RCA's technical operations but also on the contributions of its diverse companies. We constantly try to get articles looking at the business perspectives of a particular operation, and more of these will be published in the future.

In response to the Survey question on "technical information not directly related to job duties but important to keeping broadly abreast of the state of the engineering art and science in a particular field," *TREND* scored about average. *TREND*, as The Research and Engineering News Digest of RCA, has as another goal to make engineers and scientists aware of the latest technical achievements in the Corporation—the whole Corporation. We hope to include more of the technical work going on in the Corporation that is not highlighted elsewhere. How? By periodically asking our readers for "news tips" on developments they want to share with the total technical community at RCA, and by utilizing the Editorial Representative network to help get inputs.

As for supplying technical information that is directly relevant to the performance of present job duties, *TREND* scored below average and it should. We don't pretend to help an engineer do a specific job, but do attempt to point out where a colleague may be doing comparable work and how additional information can be obtained.

TREND was rated above average as an information source about professional achievements, i.e., society work, awards, honors. We will continue to concentrate on major technical honors and achievements, but leave coverage of the bulk of professional accomplishments to the *RCA Engineer* journal and other media such as Technical Excellence newsletters.

The survey showed that 10% of the respondents did not receive *TREND*. The news digest is not sent directly to each engineer but is disseminated via a distributor network. A person at each location is charged with the responsibility of breaking down a bulk shipment and forwarding copies to engineering departments at that location. As engineers move around in their divisions or change locations, they should advise the *TREND* office of their new addresses to ensure uninterrupted service. Distributors are asked to poll periodically the engineering departments they service to make sure *TREND* distribution is adequate.

Indications of unsatisfactory distribution uncovered in the Survey are being followed up. All Survey respondents should receive their own copy of *TREND*, as the engineering community is the prime audience for the news digest.

Although content of a digest is primary, its readability is enhanced by its look. *TREND* readers scan 46% of the digest and read 41%—not bad, but the ratio should be shifted to more "read." With Editorial Board and Staff help, we are attempting to make *TREND* more interesting and lively by improving its graphics (typography, photos, cartoons), content (shorter stories to gain more variety in coverage of all RCA's operations), and by running specials (technology quizzes, guest editorials). A highly valued feature in *TREND* is the organization chart. Readers are interested in following the progress of their colleagues. More charts are planned in upcoming issues.

In summary, then, these Survey results will serve as a guideline, along with suggestions from the *TREND* Editorial Board, to ensure that readers get balanced and adequate coverage of RCA's technical and related business activities in each issue. But perhaps more importantly, we can't publicize your achievements if we don't know about them. *TREND* is a "readers' digest" in the sense that it reflects its readers' work. Our output is your input. We look forward to hearing from you if you feel you have an achievement that can help others at RCA in their work.

RCA Technical Abstracts
Doris Hutchison, Editor
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Ext. PY-5412

The survey showed that many of those reading *RCA Technical Abstracts* do follow through by obtaining copies of documents abstracted therein. However, it was a surprise to find that 21% of those replying have encountered so much delay or difficulty in getting documents that they have given up trying. Copies of all documents abstracted in *RCA Technical Abstracts* are available, and there is no reason why you should not be able to obtain them. The best source, of course, is your librarian, who should be able to get any RCA document for you fairly quickly. If you experience any difficulty in obtaining documents, we would like to know about it.

RCA Technical Abstracts is of value to 37% of the respondents; this constitutes the lowest ranking of the four sources considered. One reason for the low ranking is that 55% of the respondents do not use *RCA Technical Abstracts* because they either do not know what it is (26%) or do not have access to it (29%). To help remedy this situation, a reprint of an *RCA Technical Abstracts* cover with a description of its purpose, coverage, how to use it, and where to find it was included with an *RCA Engineer* mailing. Hopefully, some of the 55% mentioned above will now look for *RCA Technical Abstracts* in their library, ask their engineering management to put them on their circulation list, or, if not otherwise available, request to be put on the distribution list. A number of such requests have been received and honored.

RCA Libraries
Contact your librarian, or
Doris Hutchison
Corporate Engineering, Cherry Hill, N.J.
Ext. PY-5412

The libraries rate very high in this survey and maintain an image of providing business, professional, and technical information to 81-93% of the respondents. There is little question that their value ranks highest among the information sources covered in the survey.

Why does RCA provide these technical information sources?

RCA Engineer—A bimonthly technical journal that publishes state-of-the-art reviews, tutorials, and other technical, and business-oriented papers. It provides an in depth look at what's going on at RCA and helps you update your knowledge of the electronics field. It also provides a forum in which you can publish to enhance your professional reputation. For more information, call John Phillips, Cherry Hill, Ext. PY-4254.

TREND—a monthly briefing of what's going on technically at RCA, what RCA's businesses are doing, and what services, products, and other aids are available to support your work. For more information, call Frank Strobl, Cherry Hill, Ext. PY-4220.

RCA Technical Abstracts—A monthly company-private abstract bulletin of RCA's proprietary technical reports and publications. It cites author, source, and document-number and includes RCA patent disclosures and MIT research reports as well as the RCA papers and reports. Annual cumulative indices are also available, starting with 1968. For more information, call Doris Hutchison, Cherry Hill, Ext. PY-5412.

RCA Libraries—The highly skilled librarians in RCA's technical libraries can get just about any piece of technical information you may need or desire. If your location doesn't have a library, your divisional library is willing to support you. For more information, call your librarian or Doris Hutchison, Cherry Hill, Ext. PY-5412.

All locations employing large numbers of engineers are serviced by an RCA technical library operated by a highly skilled professional librarian.[4] Many other locations have modest libraries or technical information collections staffed on a part-time basis. This type of information facility could also be useful at several additional locations. Engineers in locations lacking library facilities can use the major library of their operating unit; at present, about 7% of the survey respondents take advantage of a remote library.

Some of the needs expressed by survey respondents are now being provided at several locations. For example, on-line computer searching is now available at Moorestown, Princeton (Laboratories and Astro-Electronics), Lancaster, Indianapolis, and Burlington; soon to be available in Camden, with other libraries considering this service.

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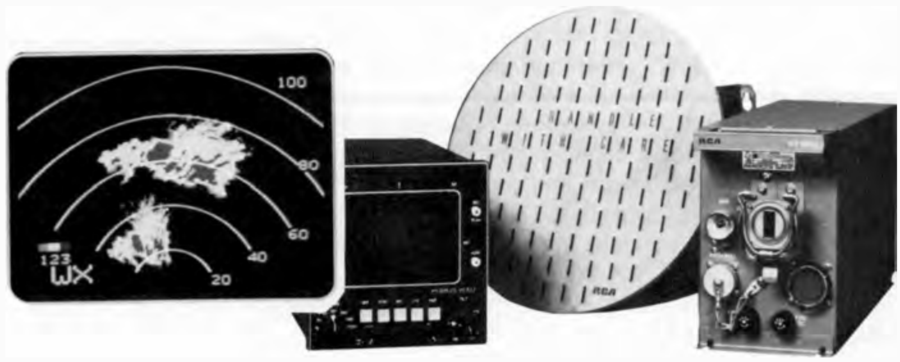
The color weather radar indicator—a 1978 David Sarnoff Award winner

Color displays for airborne weather radar

Pilots recognize potentially dangerous storms more readily when the storm locations are displayed in color.

R.H. Aires | G.A. Lucchi



In 1977 RCA introduced weather radar systems with color indicators for both commercial air carriers and general-aircraft users. The use of color has significantly improved the pilot's ability to recognize potentially dangerous storms. It has also improved the radar's usefulness in the ground-mapping mode, where the pilot looks at the terrain below instead of the weather ahead. But before describing this advance, some background on weather radar is necessary.

Relating rain density and turbulence

Weather-radar systems used in the air-carrier and general-aviation industry measure the rainfall density that exists within a storm cell—they are not able to assess turbulence directly.

Experience has shown, however, that storm cells containing rainfall rates of over 11.5 millimeters per hour quite often produce enough turbulence to cause aircraft structural damage or passenger injury. Therefore the FAA advises pilots to stay at least 20 miles away from storms with rainfall rates exceeding 11.5 mm/hr.

The radar return from a storm depends upon the backscatter from the raindrops.

Eq. 1 is the basic radar range equation used to calculate the detectability of a specific radar target.

$$P_r = P_t G^2 \lambda^2 \sigma / [(4\pi)^3 \; R^4 L] \qquad (1)$$

where

P_t = transmitter peak power
G = antenna gain used both for receiving and transmitting
λ = radar carrier wavelength
σ = target radar cross section area
R = one-way range between radar and target
P_r = received power from the target
L = system losses, correlation gain, etc.

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This equation is derived from the theoretical considerations with the radar target consisting of a solid, highly conducting surface of generally spherical shape. In order to apply this equation to meterological-type targets, it must be modified to reflect a three-dimensional fluid-impregnated volume representative of a storm cell core.

The radar backscatter coefficient Z for spherical raindrops has been empirically established. The coefficient is a function of the sixth power of the raindrop diameter and the number of raindrops in a specific volume. It is denoted by

$$Z = \sum_{i=1}^{N} D_i^6$$

and is inversely proportional to the fourth power of the radar carrier wavelength and proportional to the second power of absolute value of the dielectric constant, K, of water. Since the backscatter coefficient is also proportional to rainfall rate, the relationship* $Z = 200\, r^{1.6}$ is used to define the reflectivity, where Z is in mm^6/m^3 and r is the rainfall rate in mm/hr. For the pencil-shaped radar antenna beam generally used on airborne weather radar systems, the resultant pulse volume can be defined as $(\pi/8)R^2\theta^2 cT$, where R is the radar range, θ is the antenna beamwidth, c is the speed of light, and T is the transmitter pulsewidth. The resultant radar target backscatter cross section σ is the pulse volume times the factors which relate to the meteorological targets described below.

*This relationship pertains to Strataform-type storms; $Z = 55\, r^{1.6}$ is sometimes used for convective storms.

This backscatter coefficient is shown in Eq. 2.

$$\sigma = (\pi^5/\lambda^4)\; ZK^2(\pi/8)R^2\theta^2 cT \qquad (2)$$

By substituting σ from Eq. 2 into Eq. 1, converting the terms into appropriate values, and converting the equation into a dB format, the weather range equation for a beam-filling target is shown in Eq. 3. This format makes the equation suitable for relatively simple graphing and so assists tradeoff analyses in design.

$$P_r = 10\log P_t + 20\log\theta + 10\log T + 10\log Z - 20\log\lambda - 20\log R + 2G - L - 168.25 \quad \text{(dB)} \qquad (3)$$

where P_r is in dBm, θ is in degrees, Z is in mm^6/m^3, R is in nautical miles, P_t is in kW, T is in μs, λ is in cm, G is in dB, and L is in dB.

For a storm cell whose diameter does not fill the radar beam, Eq. 3 must be modified by substituting the non-beam-filling volume equation $(\pi/8)d^2cT$ for the beam-filling volume equation $(\pi/8)R^2\theta^2cT$ into Eq. 2, where d is the storm cell diameter. The same procedure used to establish Eq. 3 yields Eq. 4 for non-beam-filling storms.

$$P_r = 10\log P_t + 20\log d + 10\log T + 10\log Z - 20\log\lambda - 40\log R + 2G - L - 133.08 \quad \text{(dB)} \qquad (4)$$

All terms in Eq. 4 have the same units as in Eq. 3 except d, which is in nautical miles.

Eqs. 3 and 4 are used to calculate the received power which appears at the input to the receiver for the range and radar parameters selected for a specific storm cell density.

Both range equations are plotted in Fig. 1 using the system parameters for the RCA PriMUS-400 ColoRadar system with an 18-inch flat-plate antenna. It can be seen that the received power decreases at 6 dB per octave of range at distances up to the point where the 3-nautical-mile-diameter storm-cell model changes from beam-filling to non-beam-filling. At greater ranges the received power decreases at 12 dB per octave of range.

Pilots must avoid storms above a certain intensity, so radar displays must make these storms stand out.

The radar meteorology industry has related rainfall rates to the storm intensities (Table I). The table also gives the colors RCA uses to indicate these rainfall rates.

RCA's background in weather radar

RCA has been producing airborne weather radar systems for commercial air carriers and general-aircraft users since 1955. The first system produced was the well known C-band AVQ-10, which is still being used by many of the world's airlines. Since that time, most of the airborne weather radar systems have been designed to operate at X-band. So far, RCA has produced a total of eleven different types of X-band and two types of C-band radars; they are used in aircraft ranging from wide-bodied jets down to the smallest twin-engine aircraft. RCA's most recent weather-radar advancement is the PriMUS-400 ColoRadar described here.

Table I
Radar measures rainfall, which can be correlated to storm turbulence. (Radar cannot measure turbulence directly.) Radar meteorology industry has grouped rainfall rate (and thus turbulence) via this table. RCA has selected colors in the table to indicate the different storm levels.

Storm intensity	*Rainfall rate*	*Display color*	*Digital level*
Drizzle	0.25 mm/hr	black	0
Light	1.0 mm/hr	green	1
Moderate	4.0 mm/hr	yellow	2
Industry standard pilot alert	11.5 mm/hr	red	3
Heavy	16.0 mm/hr or greater	*	*

*Storm levels with rainfall rates greater than 11.5 mm/hr are shown as the number 3 level regardless of their intensity.

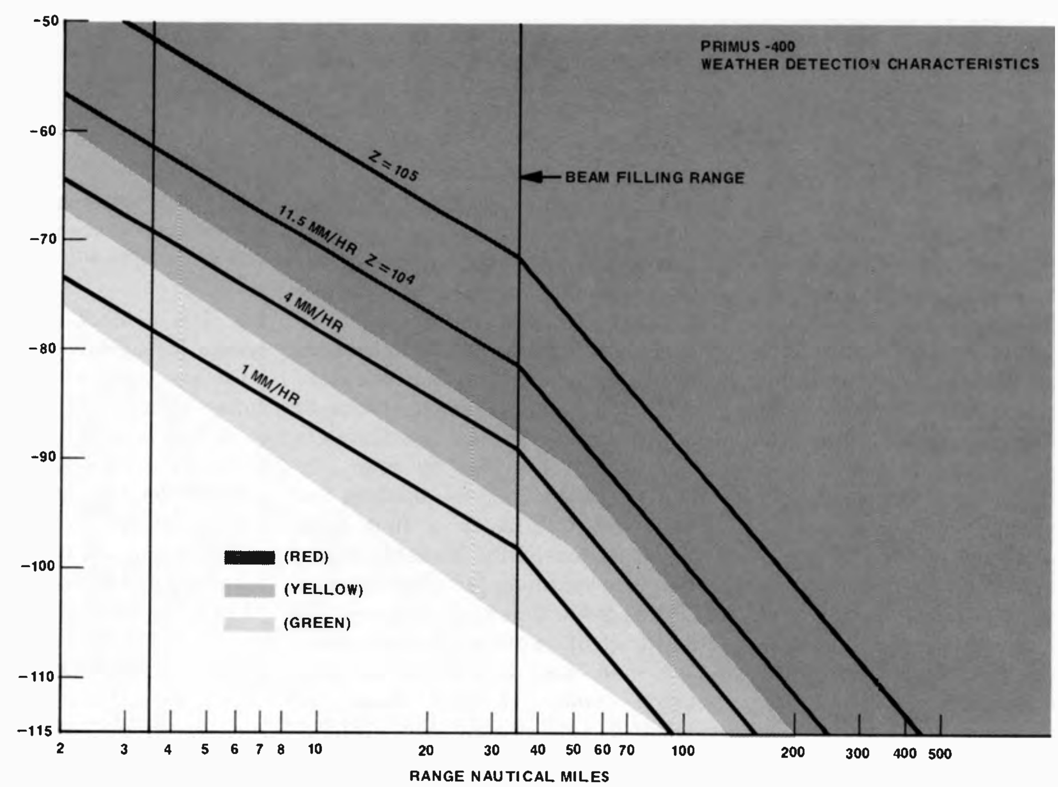


Fig. 1
Weather detection characteristics of the PriMUS-400 ColoRadar. The four solid lines show the returned power from storms with different rainfall rates. The 11.5 mm/hr. storm is potentially dangerous. System identifies levels of storm intensity by different colors on the display. The vertical "beam-filling" line, which defines 3-nautical-mile-wide storms that do or do not fill up the radar beam, also establishes the break point between the two radar range equations. The shaded areas show how the receiver gain is shaped.

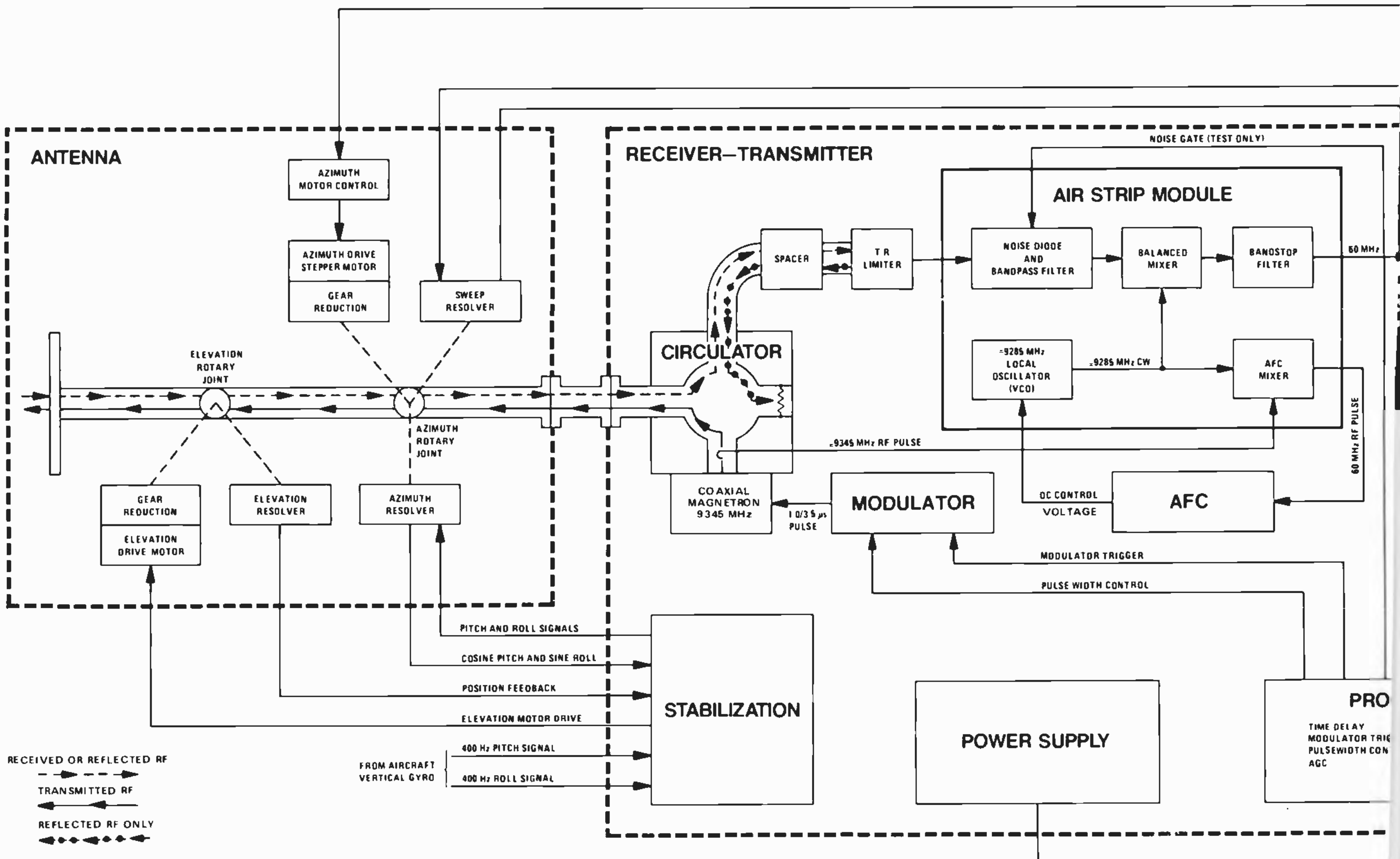


Fig. 2
PriMUS-400 system. Radar pulse (variable width for looking at ground or weather) goes through circulator to stabilized antenna, then returns through antenna and circulator. After signal processing and amplification, the returned signal is digitized to one of four storm-intensity levels, scan-converted from polar to x-y coordinates, and displayed on the color crt.

Meteorologists have established that storms whose rainfall rate equals or exceeds 11.5 mm/hr (a Z factor of 10^4) should be avoided by aircraft. As a result, in monochrome displays, areas with this Z level are blinked between the brightest level (number 3) and then off so that the pilot can easily distinguish the storm's position. In the color display system, this level appears as red, with a pilot option to have the area blinked between black and red. In order to determine where lesser rainfall rates are located in a storm cell, the 4 mm/hr signal level is detected and displayed as the 2nd from the brightest (number 2) in the monochrome indicator and in yellow for the color indicator. The 1 mm/hr storm is indicated as the lowest level (number 1) on the monochrome indicator and green on the color indicator. In this manner, the pilot can easily determine where to fly to avoid storms of varying intensity levels. The "drizzle" level is not shown on the display because its turbulence intensity is insufficient to be of concern.

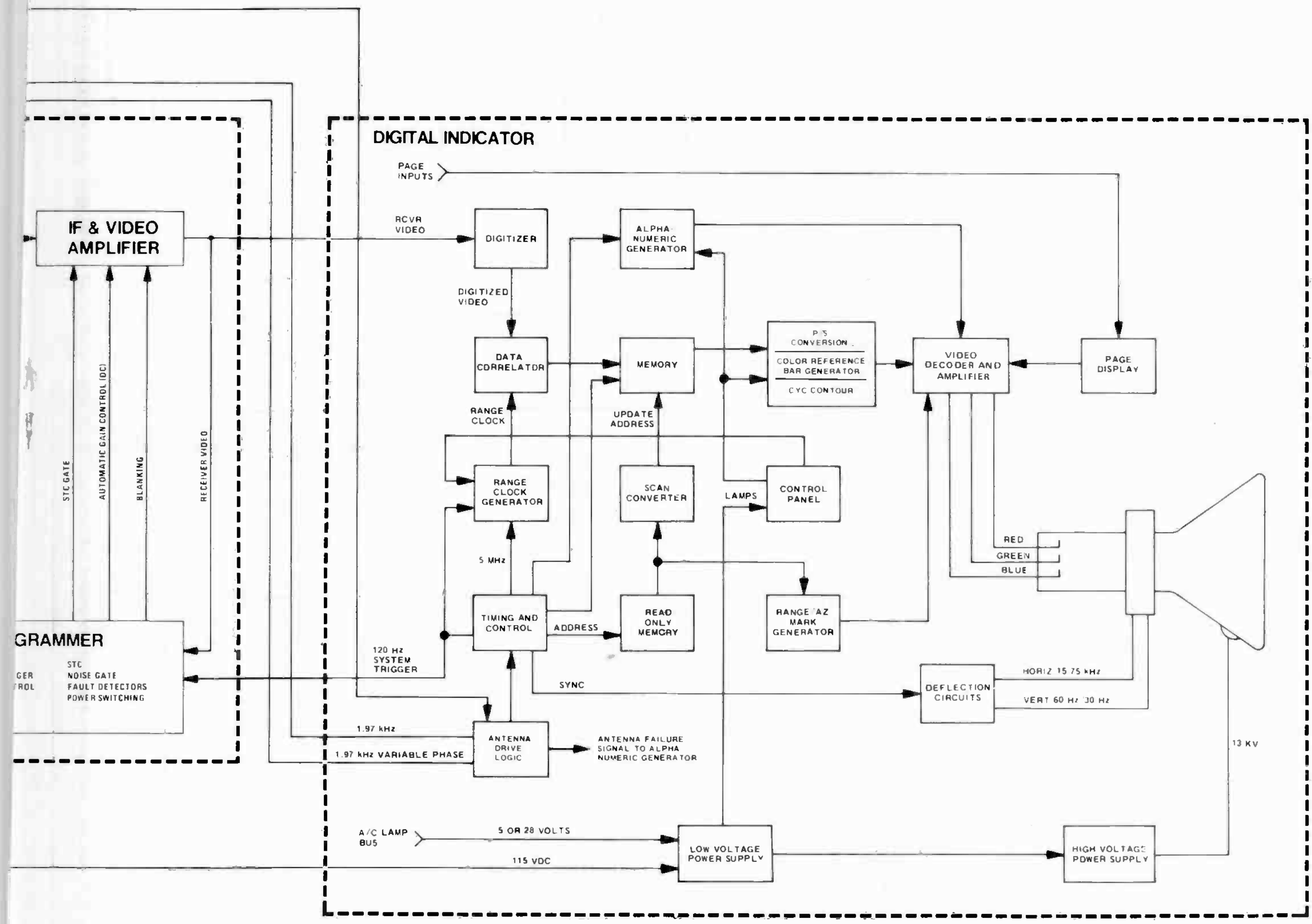
PriMUS-400 ColoRadar

On March 15, 1977 RCA announced the first general-aviation airborne weather radar system with a color indicator. The acceptance of this system by pilots has been overwhelming, primarily because the use of color greatly simplifies the recognition of displayed storm intensities. In addition to the advantages provided by color, the resolution of the display used in the PriMUS-400 ColoRadar is four times better than previously available digital storage type indicators. Another feature of the PriMUS-400 ColoRadar is the use of a different set of colors (cyan [blue-green], yellow, and magenta) in the ground-mapping mode. In this mode the transmitted pulsewidth and receiver bandwidth have been optimized to take full advantage of the increased display resolution. The overall result is much better ground-mapping than previously available. Major design considerations for the primary functions of the PriMUS-400 ColoRadar system will now be described.

The major elements of the PriMUS-400 system are the receiver/transmitter, the indicator, and the antenna.

Fig. 2 is a block diagram of the radar system. A magnetron generates microwave pulse energy at 9345 MHz and the circulator then directs it to the antenna, where it is radiated to illuminate the target. Reflected energy from the target is intercepted by the antenna and directed by the circulator to the microwave mixer. The mixer converts the microwave frequency to a first i.f. of 60 MHz. After amplification at 60 MHz, a second conversion to 10.7 MHz occurs within the i.f. amplifier to achieve the desired bandwidth prior to video detection. An AFC adjusts the receiver microwave local oscillator to track the magnetron frequency.

The detected video signal is digitized in the indicator to four discrete levels. After digital integration of the returns from four pulses, the data is scan-converted from polar-coordinate (rho-theta) format to tv



(x-y) format for storage in a RAM memory. Readout of the RAM memory is in standard tv format at a 60-Hz field rate. A decoder turns on the appropriate red, green, or blue gun of a color CRT, depending on whether the data represents a 0, 1, 2, or 3 level.

External video signals can be added to the radar data by video mixing at the video amplifier. Range and azimuth marks and even alphanumeric information can also be added to the display by video mixing. The indicator logic generates timing signals to trigger the transmitter and to drive the antenna azimuth stepper motor. The antenna elevation motor is driven from signals derived from the aircraft attitude reference (vertical gyro) to stabilize the antenna against pitch and roll maneuvers and permit manual control of the antenna elevation angle for ground mapping.

The transmitter has a variable pulsewidth.

A 10-kW coaxial magnetron has been selected for reliability and frequency-stability characteristics. This magnetron has been used in the top-of-the-line RCA general-aviation weather radars since the introduction of the AVQ-21 in 1970. It maintains nearly full power output until end-of-life because of its conservative cathode loading. The large coaxial cavity is much less subject to particle build-up than the older strap-vane design and therefore has less tendency to change frequency with age. A solid-state line-type modulator with an SCR switch provides the required 4.7-kV pulse for the magnetron.

In the weather mode, the transmitter pulsewidth is 3.5 μs. For optimum performance this pulsewidth requires an i.f. bandwidth of approximately 350 kHz. From Eqs. 3 and 4 it can be seen that the received power (P_r) is greater with a wider pulsewidth. A pulsewidth of 3.5 μs sacrifices little weather resolution, since the established model storm cell is 3 miles or 37 μs in diameter. The 3.5-μs pulsewidth is therefore a reasonable compromise between sensitivity and resolution.

In the ground-mapping mode, the resolution of small targets is limited by the pulsewidth and receiver bandwidth. The selection criteria here was a tradeoff with the display resolution, which is determined by the size of the digital memory. In the PriMUS-400 ColoRadar the digital memory consists of two planes of 64k bits each. The screen therefore can be divided into 256 × 256 cell locations, with the range resolution determined by dividing the selected range scale into 256 cells. On the 25-mile-range scale the smallest increment stored is 25/256 miles or approximately 0.1 mile, which is equivalent to 1.2 μs. A 1-μs pulsewidth is used in the ground-mapping mode for selected range scales of 50 miles or less. On the 100-, 200-, and 300-mile ranges the pulsewidth is increased to 3.5 μs for increased range performance and because the display is the limiting factor on resolution.

The pulse-repetition frequency (PRF) is determined by the desired display resolution and the antenna scan rate. The

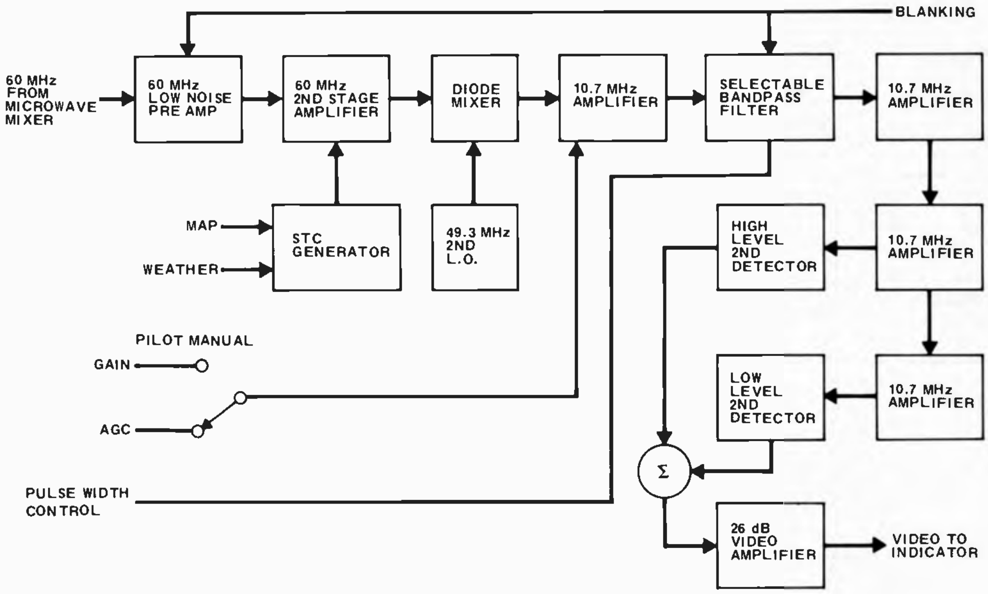


Fig. 3
I.F. amplifier optimizes system sensitivity by generating a second i.f. center frequency of 10.7 MHz. Sensitivity time control (STC) adjusts gain with range; manual gain control allows pilot to vary color-level settings and see which part of storms are most intense.

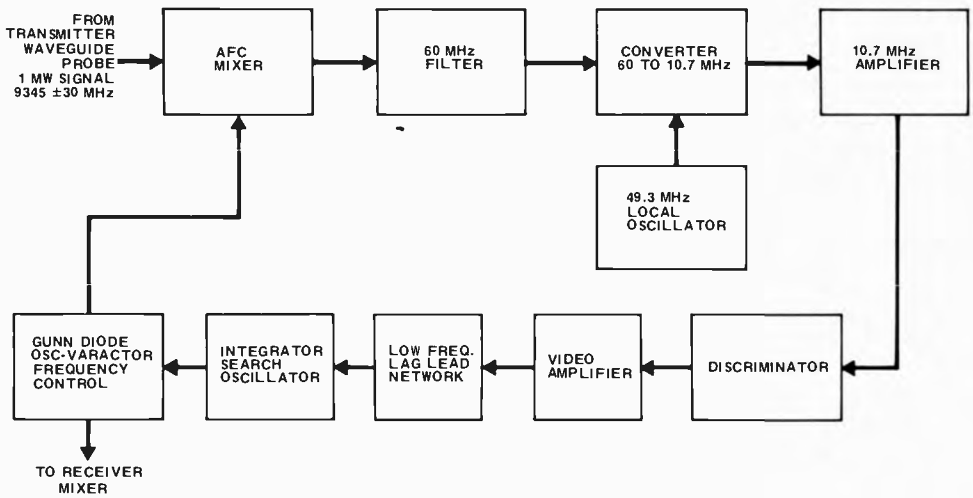


Fig. 4
AFC system essentially guarantees "lock-on."

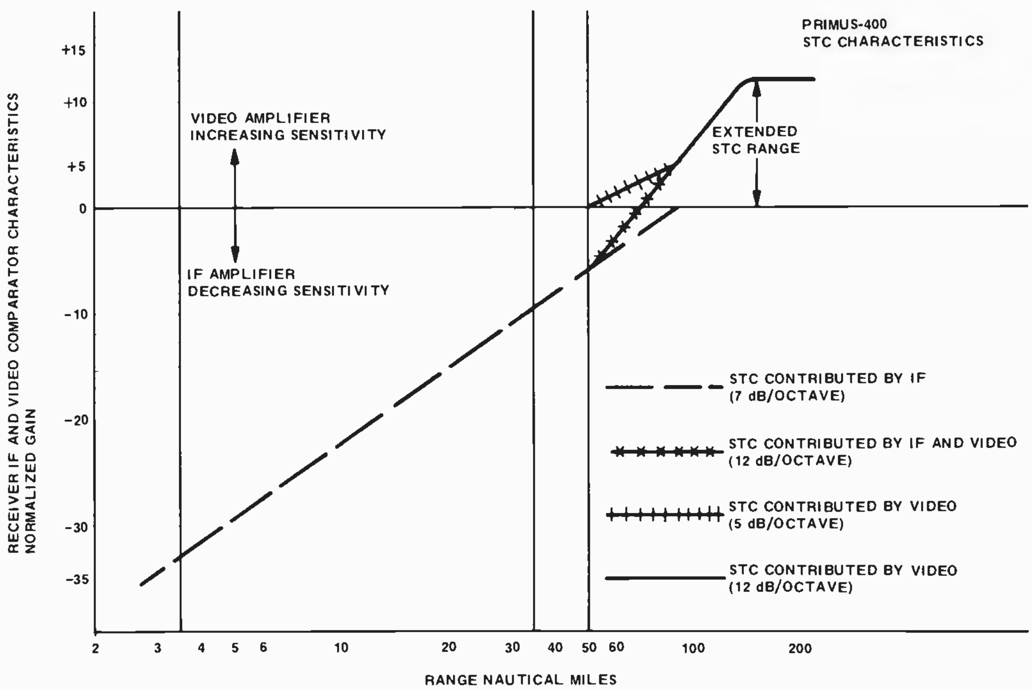


Fig. 5
Perceived-power/range slope can be varied at the i.f. amplifier or video amplifier. Beyond 50 nautical miles range, additional sensitivity comes from varying the reference voltages of the comparators.

PriMUS-400 antenna scans 120 degrees in 4.3 seconds. For an azimuth resolution of one quarter of a degree, a PRF of 120 Hz is required.

The receiver has a very good noise figure.

The PriMUS-400 achieves a 7-dB noise figure by using a bandpass filter to reduce the noise at the image frequency along with low-noise hot carrier diodes, a balanced mixer to reduce feedthrough of local oscillator noise, and a low-loss circulator and TR device. An isolator between the Gunn diode local oscillator and the mixer reduces frequency pulling. A separate AFC mixer permits accurate adjustment of the sampled magnetron frequency amplitude. This configuration provides a system noise figure at least 1 dB lower than competitive systems and provides 40-dB rejection of signals at the image frequency.

A 60-MHz first i.f. amplifier center frequency permits the practical design of the X-band bandpass filters used to reduce image-frequency noise mentioned in the previous section. In order to achieve the 350-kHz predetection receiver bandwidth, a second local oscillator and mixer generate a second i.f. center frequency of 10.7 MHz to optimize the system sensitivity when in the 3.5-μs-pulsewidth weather mode. Sensitivity time control (STC) is generated in the STC generator (Fig. 3) and injected into the second stage of the 60-MHz amplifier. The STC is adjusted for approximately 35-dB receiver gain attenuation at 3 nautical miles and has the gain increase at a rate of 7 dB per octave of range, reaching maximum gain at approximately 90 nautical miles. The adjustment allows for 3 dB of internal system degradation and 1 dB per octave of range to account for atmospheric attenuation from intervening rain up to 35 nautical miles, as shown in Fig. 1.

AGC, applied to the first 10.7-MHz amplifier, is established by sampling the video output signal at a range beyond the maximum range of expected radar signal returns. A pilot-operated manual gain-control voltage is applied in lieu of AGC when the gain is turned out of the calibrated preset position. The manual gain control can determine which of the 3-level (red) areas contain the most intense rain. While in this variable-gain position, an alphanumeric warning on the indicator reminds the pilot that the system is not calibrated for the standard rainfall rates. The gain control is also very useful for optimizing target recognition when in the ground-mapping mode.

A separate X-band mixer diode provides a sample from every magnetron pulse at 60 MHz, which is then down-converted to a 10.7-MHz amplifier and discriminator. When not "locked-on," the control voltage automatically sweeps the X-band local oscillator ±30 MHz until "lock-on" is established. The AFC servo loop is designed to achieve the highest stable gain possible with a 120-Hz sampling frequency. More than a 10:1 range of a "−2" gain vs. frequency slope is used in the AFC servo loop is achieve a high effective K_v. The average search sweep rate of 10 MHz/second is slow enough to essentially guarantee "lock-on" with this loop characteristic and a discriminator bandpass of 1.5 MHz. Fig. 4 is a block diagram of the AFC.

Three comparators determine the 0, 1, 2, and 3 levels corresponding to rainfall less than 1 mm/hr, 1 mm/hr, 4 mm/hr, and 11.5 mm/hr, respectively.

Fig. 1 shows that the power-received/range slope is 7 dB/octave at less than 50 nautical miles range and 12 dB/octave beyond 50 nautical miles range. Within the range of STC, 7 dB/octave is achieved by varying the i.f. gain, as shown in Fig. 5. Beyond 50 nautical miles range, additional sensitivity is provided by varying the reference voltages, and thus the sensitivity, of the 2- and 3-level comparators to achieve a total of 12 dB/octave of range up to 150 nautical miles. Since the PriMUS-400 displays red for a 3-level signal strength, the pilot is accurately warned of 3-level storms up to a range of approximatley 150 miles (18 minutes away at a jet speed of 500 knots).

A four-pulse digital integrator with a 3-out-of-4 algorithm reduces the false-alarm rate, thus permitting the gain to be increased by 3.8 dB before the false-alarm rate is objectionable. A minimum discernible signal (MDS) of −115 dBm can be achieved with the PriMUS-400 when receiving a pulsewidth equal to a standard (37-μs) storm cell.

Range and azimuth data are collected in polar (rho-theta) coordinate format, but displayed in x-y format.

Until recently, most airborne radar displays were scanned in the rho-theta format (Fig. 6a), which has the disadvantage of

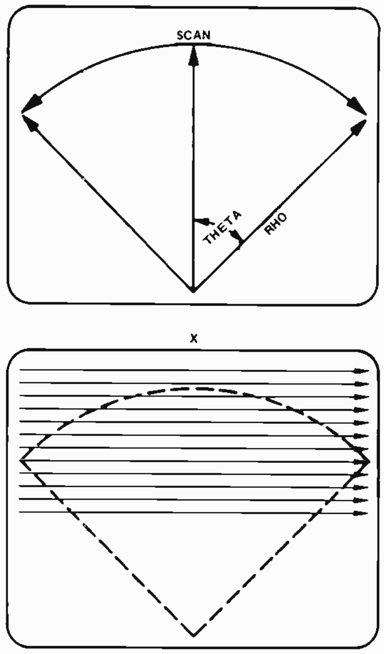


Fig. 6
Range and azimuth data is collected in polar coordinates (top), but displayed in tv-scan coordinates (bottom). Digital storage makes this display method practical and produces uniform brightness and resolution over the entire displayed area, something not possible with the polar-coordinate display.

non-uniform resolution over the area of display. Near the origin of the display, the data is crowded, and at the edge of the display, it is spread out much as the spokes of a wheel. With the advent of digital data storage in solid-state random-access memories, many advantages of x-y scan became practical. Some of these advantages are:

- uniform brightness and resolution over the displayed area;
- efficient deflection and high-voltage system;
- compatibility with a tv raster to combine data from other sensors and systems; and
- compatibility with the requirements of a line-screen color CRT.

A preprogrammed read-only memory steers the received signals from each transmitted pulse to the appropriate location in a random-access memory corresponding to the antenna angle and target range. Scan conversion is achieved by reading the random-access memory in x-y format, as shown in Fig. 6b. The readout is performed at standard tv rates, thus providing a flicker-free display using a conventional tv crt.

Fig. 7
High-resolution dot pattern for range azimuth markers is difficult to produce on a 525-line tv raster. Special LSI circuit makes the dots appear as smooth lines.

The video display has high-resolution azimuth marks; it also accepts external inputs for pilot checklists and other data.

Very high video bandwidth is required to draw smooth arcs representing range marks and straight lines for azimuth marks on a 525-line tv raster. A custom large-scale-integrated circuit was developed with RCA's Solid State Technology Center. This IC provides 50-ns video pulses to generate a high-resolution dot pattern that appears as smooth lines on the display (Fig. 7). The color of these lines and marks is cyan in the weather mode and green in the map mode for good color contrast. Alphanumerics generated by a character generator identify the range marks, selected mode, and special alerts. An external video input connector allows the indicator to be time-shared for other functions such as checklist, navigation information, optimum flight profiles, and other tv-formatted data.

The antenna must have good stabilization with the high-resolution color display.

The antenna can be scanned through 120 degrees in azimuth and 60 degrees in elevation. The normal pattern is a horizontal line scan. A two-phase stepper motor drives the azimuth axis, based on command pulses from the indicator. The direction of scan is controlled by the phase relationship. A feedback signal determines when the antenna is passing the dead-ahead position and this signal is compared with the indicator command to verify synchronization. If an error exists, the radar data is blanked and the letters ANT are flashed on the screen.

To maintain a scan pattern that is fixed in space relative to the earth's surface, pitch and roll signals received from the aircraft attitude-reference system are applied to an elevation servo system. The use of two axes of freedom (typical in most general-aviation aircraft) means that the antenna elevation servo must continuously correct for the aircraft's roll and pitch. Brushless resolvers and a two-phase ac motor are used in the elevation axis servo for long life. A major improvement over previous stabilization designs has been achieved through the use of good servo design practices to achieve a high effective loop gain (K_v), which became more important when the high-resolution color display was introduced.

The waveguide slotted-array antenna used obtains 70% aperture efficiency with sidelobe levels 25 dB or more below the mainlobe. These two characteristics are extremely important to maximize the range performance of the radar and to minimize ground clutter when looking for weather.

Summary

The PriMUS-400 ColoRadar system described in this paper has introduced many new features that have led to its immediate popularity in the general-aviation marketplace. The most important feature was the introduction of a color indicator with 4 times the display resolution of previous digital storage systems. For a lightweight radar system, the 150 nautical miles of storm intensity calibration provides a capability not previously found in the most sophisticated large and expensive airline-type weather radars.

Ray Aires is Chief Engineer of Avionics Systems. Under his guidance, RCA has introduced the PriMUS-20 and -30 weather radars, which were the first to employ x-y scanned indicators providing alphanumeric information outside the radar presentation. Avionics Systems' PriMUS-21, -31, and -50 were developed specifically for helicopter applications. Most recently, he was responsible for RCA's introduction of the first weather radars with color indicators, including the PriMUS-90 for commercial air carriers and the PriMUS-300 and -400 for general aviation.

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George Lucchi has over 20 years of radar experience with RCA. His recent projects include a number of distance-measuring equipments and transponders, plus contributions to a number of weather radar systems—the AVQ-47, -21, and -30 systems plus the PriMUS series.

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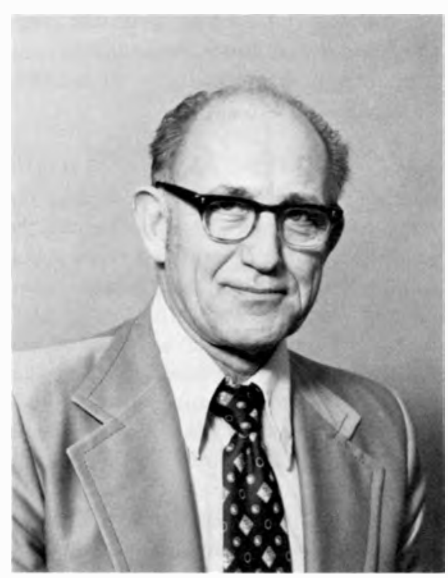

Advanced antenna design reduces electronic countermeasures threat

The expansion of electronic countermeasures has changed the ground rules for air-surveillance radar design. Low-sidelobe radar is a good example of electronic counter-countermeasures at work.

R.M. Scudder

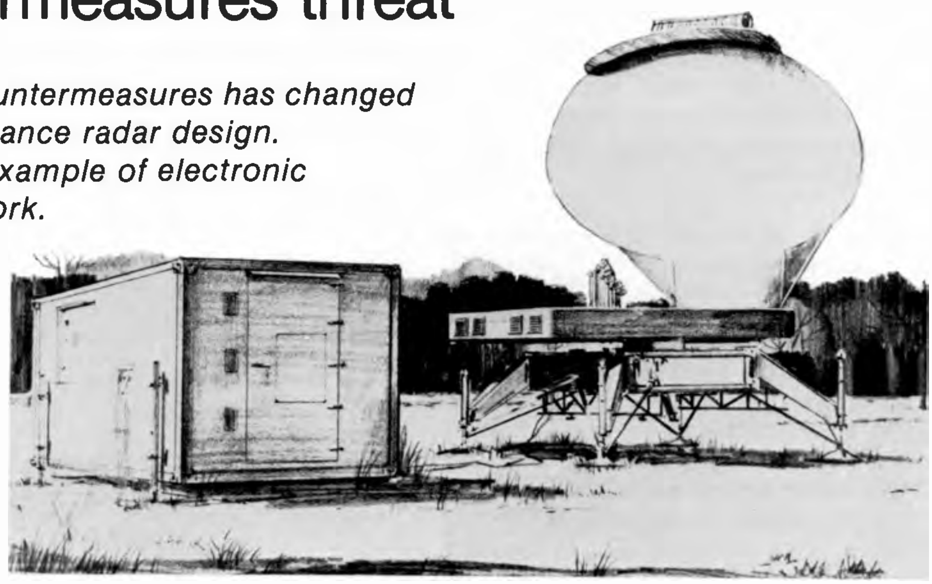

Fig. 1
Stepped-beam reflector antenna as it would be emplaced as an element of a tactical radar system. Typical rotation rate is 6 rev/m. Transportable radar shelter at left contains radar transmitter plus operator display and control functions.

The demands on radar systems are ever-changing, and nowhere is this more true than in those made on high-performance radar operations by the expanding environment of active countermeasures. The sophistication of advanced ECM (electronic countermeasures) equipment, and the recent addition of ARM (anti-radiation missiles) can, in combination, severely compromise the effectiveness of the standard surveillance radar systems built in the 1950s and 60s.

Countering the countermeasures involves two principal approaches:

1) *Signal diversity*—varying the frequency, power, polarization, or waveform of the radar signal so that the necessarily limited jamming capability of the ECM equipment receives more variety in received signals than it can counter.

2) *Sidelobe suppression*—maintaining the sidelobes that inevitably accompany the main radar beam at such low levels that the ECM equipment cannot generate effective blanking countersignals on these lobes.

Implementing these approaches takes a variety of mechanizations, any or all of which can be combined in advanced-design, sophisticated systems (e.g., multipurpose phased-array radars). Such systems, of course, are costly, usually large and therefore relatively immobile, and impose special power and signal-processing requirements. These requirements combine to preclude such an approch for tactical surveillance radars, which must be highly mobile and easy to set up and operate in forward areas.

But it *is* possible to apply ECCM (electronic counter-counter-measure) techniques to tactical systems, using straightforward modifications to standard radar design to achieve really effective operations in advanced ECM environments. This paper addresses such an approach and describes the preliminary development of a paraboloidal-reflector, stepped-beam antenna system that promises excellent radar performance in an environment of modern, advanced ECM.

Antenna design and the environment

The antenna configuration described here is compatible with the constraints associated with the operating environments for today's tactical radars. Attributes of the new antenna include:

very low azimuth peak sidelobes, and low average sidelobes;

polarization diversity necessary for all-weather operation;

electronically stepped beam in elevation, with mechanical rotation in azimuth, to provide full search capability with a single wideband signal-processing channel;

aperture size compatible with small-target detection and height estimation at extended ranges;

simple structure to assure minimum acquisition and life-cycle costs;

high reliability and maintainability, for operation in tactical environments;

ease of conversion into and out of the transport configuration; and

light weight for air transport.

Antenna description

A standard tactical-radar pedestal can rotate the antenna for azimuth scan, while the antenna rapidly steps its beam electronically up and down over 20 degrees of elevation scan.

Suitable for a radar using a single-channel, wideband signal processor, the new antenna achieves reduced ECM vulnerability primarily through reducing the magnitude and extent of its radiation sidelobes. Fig. 1 is an artist's concept of the antenna in operating condition. Major components include the reflector structure with edge-mounted shields (absorber panels), structural supports, the vertical array of dual-polarized feed-horns, and the associated waveguide interfaces with the transmitter and rf receiving equipment.

Other equipments located on the rotating structure include the unit containing the transmitter polarization switching and beam steering controls, the rf power distribution network, the circulator/transmit-receive limiter group, and the rf/if preamplifier group. All these items are located within the rf equipment housing structure, which also supports the feed and reflector structures in both the operating and transport configurations. A separate IFF (for identification friend or foe, a separate radar return coming from a transponder on friendly aircraft) antenna assembly is mounted at the top edge of the radar reflector.

Features of the antenna configuration include the following:

The reflector surface is 20 ft wide and 12 ft high, a section of a paraboloid with a 6.5-ft focal length, having its vertex at the bottom edge. The reflector-surface accuracy required for low azimuth sidelobe performance in operating environments is maintained by building the reflector as a lightweight monocoque structure. It is 10 in. deep, built in three sections, and joined by pin-aligned hook catches.

Absorber panels, at the top and bottom edges of the reflector, are designed to suppress wide-angle feedhorn spillover and/or edge diffraction around the periphery of the reflector surface.

The feedhorn cluster consists of seven corrugated horns, one protruding slightly above the paraboloidal axis, with the remainder below that axis. The feeds are positioned to provide secondary overlapping beams compatible with measurement of radar target-height data from the horizon to 20 degrees elevation. The crossover level between adjacent beams is at approximately −3 dB for each beam in the vertical cluster. Elevation beamwidths range from 1.7 degrees for the lower beams to 7.0 degrees for the highest-elevation beam. The beamwidth in the azimuth direction is less than 1.4 degrees for all beams. The feeds provide dual orthogonal-mode excitation to implement radar polarization diversity.

The microwave components, located in the rotating base structure, interface the antenna with its associated radar system.

The stepped-beam antenna system uses a combination of the orthogonal beam matrices, phase shifters, and power-distribution networks to provide both elevation beam steering and independent control of transmit and receive polarization modes.

Fig. 2 shows the system in block-diagram form. Stepped-beam steering in elevation is accomplished by commanded phase tapers that are identical for the orthogonal polarization paths. The polarization mode is selected by command of a mean phase difference between the two groups of eight phase shifters. Duplexing isolation between the transmit and receive paths is implemented by a 180-degree phase difference between the two groups of phase shifters, set immediately after the time of the transmit pulse to effectively "switch" the antenna from the transmitter channel to the receive path.

The power-distribution network provides amplitude weighting on various horns in the seven-horn group as a function of elevation beam steering position. Two horns are driven for the lowest beam, three for each of the next-higher elevation beams, and one for each of the three highest elevation beams.

Although the transmit and receive paths largely share common circuitry, they branch at a point where operation of the

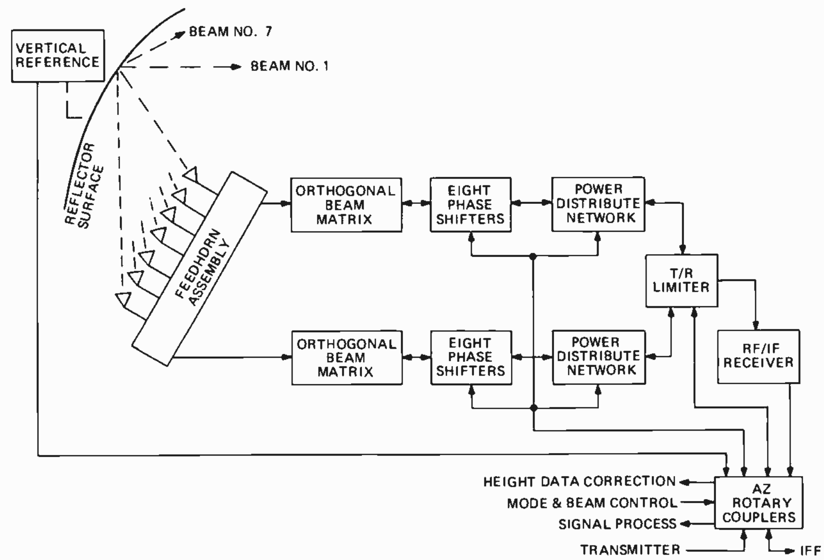

Fig. 2
Antenna subsystem block diagram indicates the general nature of the equipment housed in the rotating base assembly shown in Fig. 1. Components use rectangular waveguides, packaged to be compatible with field maintenance procedures.

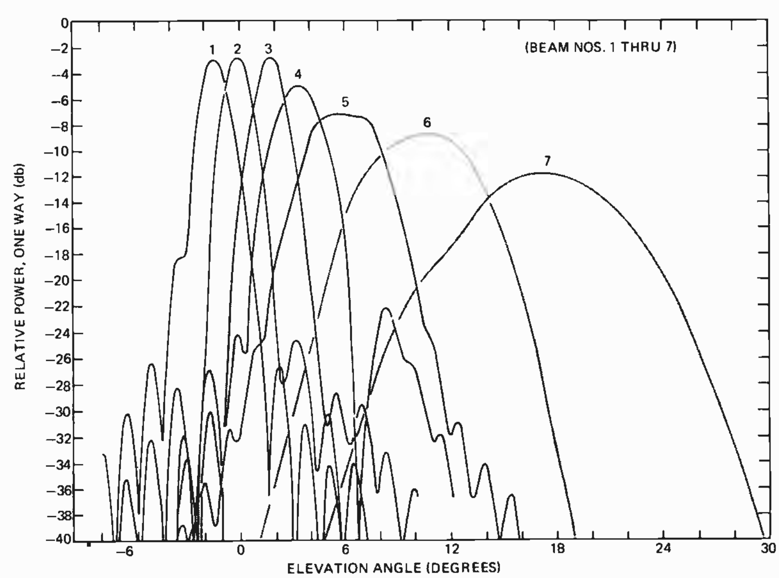

Fig. 3
Computed elevation patterns for the seven beams are shown in angular positions optimized for combined radar target detection and heightfinding functions. The beams become broader at higher elevation angle because they are created by feed assemblies displaced from the geometric focus of the paraboloid reflector.

elevation beam-steering phase shifters can permit those phasers to perform also a transmit-receive duplexing function. The antenna group includes low-noise rf and if amplification of signals for external single-channel wideband processing.

Complete receiver protection is provided by the transmit/receiver-limiter assembly. The vertical reference unit is used as the calibrated reference for measurement of target height.

For transport the antenna is disassembled and folded down. Two end sections of the reflector are unlatched from the center section and stowed flat on the base. The center section hinges down so that it, too, lies flat. The resulting transport configuration is a pallet-like assembly compatible with all modes of transportation, including C-130 cargo aircraft.

Antenna performance

Immunity of the antenna to ECM is a primary objective. The following discussion treats the measures taken to obtain a good ECCM design.

The antenna feed system was configured to provide peak azimuth sidelobes of the order of 40 dB down, while achieving the elevation beamshape required for precise target height estimation. The patterns of the antenna design were calculated using an RCA-developed computer program, DISH, a tool for observing and analyzing reflector-antenna pattern characteristics.

The elevation patterns have low sidelobes because the beams are formed by exciting adjacent feedhorns.

Elevation patterns obtained from the feed and reflector geometry were calculated and are shown in Fig. 3, which gives the elevation beam set (group) for vertical polarization. The patterns were calculated for a frequency of 3.35 GHz. The four lowest beams are formed by exciting sets of three adjacent feedhorns (the lowest beam is formed by exciting only two horns) in order to keep the elevation sidelobe levels below 24 dB and to obtain the beamwidths necessary for proper beam-crossover levels for target heightfinding functions. For example, to obtain the second-lowest beams, horns 1, 2, and 3 (Fig. 4) are excited simultaneously, with horn 2 receiving about 92 percent of the power and the remainder evenly split between horns 1 and

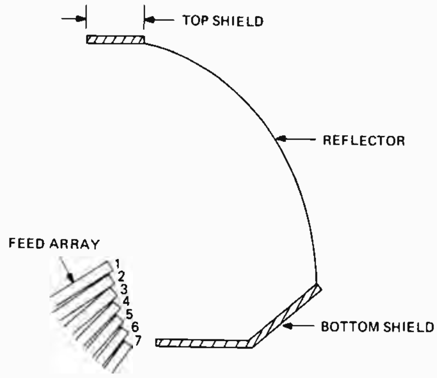

Fig. 4
Feed-reflector assembly includes several measures used to suppress wide-angle sidelobe responses in the elevation dimension. The microwave absorptive shielding reduces the radar's susceptibility to anti-radiation missiles and electronic intelligence devices.

3. Both the beam locations and crossover levels are dicatated by the required accuracy of height estimation. Elevation-pattern performance showed that, as expected, the maximum gain and minimum beamwidth correspond to a beam radiating along the axis of the paraboloid.

The azimuth patterns have a constant beamwidth and low sidelobes.

Whereas the elevation beamwidth increases as the beam is scanned in elevation from the axis of the paraboloid, the azimuth beamwidth is virtually independent of elevation beam position. This is the result of positioning the feed along the azimuth focal locus of the reflector.

In addition, the illumination of the reflector is tailored in azimuth to provide the very-low-azimuth sidelobes required for operation in an ECM environment. This constant beamwidth and low sidelobe performance is demonstrated in Fig. 5, which shows calculated azimuth patterns corresponding to beams 2, 4, and 7.

For successful operation of a radar antenna in an ECM environment, the antenna must radiate very little extraneous energy.

In other words, the antenna patterns have very low sidelobes. Low-azimuth sidelobes near the main beam were obtained by designing the feed for peak center illumination, with sharply tapered illumination toward the sides of the reflector. The edge illumination is typically −20 dB or less, resulting in peak azimuth sidelobe levels of −40 dB or lower in the absence of reflector errors or surface deformation.

Since the reflector will be fabricated as a self-supporting monocoque or honeycomb structure, manufacturing-produced surface errors will be random across the surface. The *average* sidelobe level caused by a 0.020-in. (rms) surface tolerance will

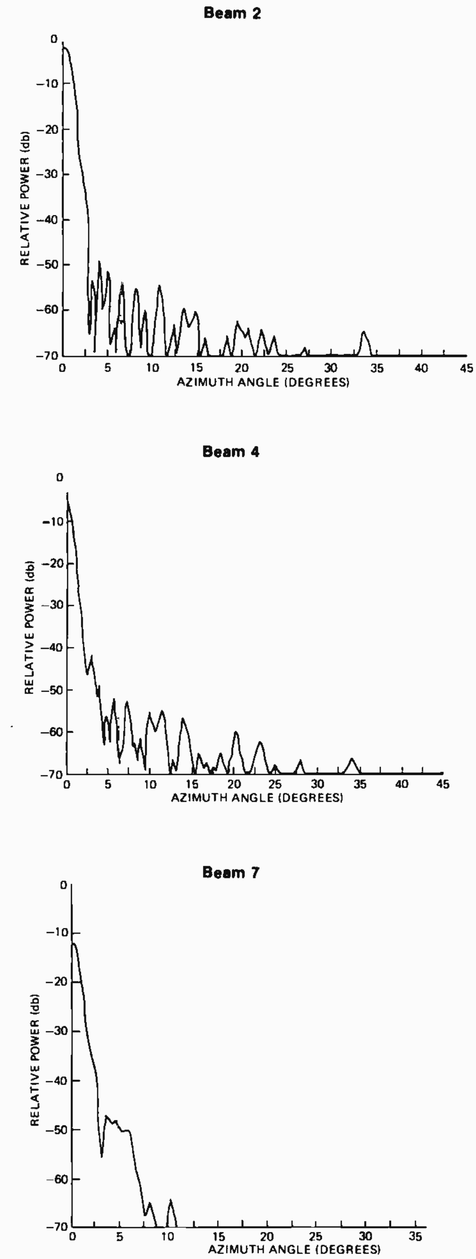

Fig. 5
Predicted azimuth patterns of elevation beam positions 2, 4, and 7 respectively. Achievement of low azimuth sidelobes is a primary objective of the antenna design. Computed patterns such as these, using the RCA simulation program DISH, guided the design to that end. Quantitatively, the objective is to provide azimuth sidelobe responses below -35 dB within 5° of the main beam, and below -50 dB outside of that azimuth angle region.

be lower than −70 dB. Wind-induced reflector deflection will lead to slightly increased sidelobe levels in the vicinity of the main beam, but for the 0.18-in. maximum deflection specified in the design, the impact on sidelobes is not significant.

Aperture blockage by the feed is often an important source of close-in sidelobes in most reflector antennas. Typically, the feed structure of a multiple-elevation-beam antenna is located directly in front of the reflector, creating an inherent blockage. As shown in Fig. 4, the feed system for this antenna is offset substantially, thereby minimizing the blockage. In the case of this antenna design, the maximum blockage area is 6 × 8 in., which results in a sidelobe level below −60 dB. The blockage contribution to close-in sidelobes is therefore negligible.

The primary contributor to wide-angle azimuth sidelobe energy is feed spillover past the edge of the reflector. In this design, spillover is controlled by a combination of directivity of the feed and reflector intercept intensity. The spillover sidelobe will be no greater than an acceptable −50 dB relative to beam peak.

Extraneous energy radiated into the conical region 45 degrees from the zenith is also caused by feed spillover. This would result in sidelobes of about −35 dB in the vicinity of the zenith. However, much of this spillover energy can be eliminated by placing an absorbing shield at the top of the reflector, as shown in Fig. 4. Suppression of spillover by this direct means has been experimentally demonstrated. Spillover energy below the bottom reflector is prevented in similar fashion, as shown in the sketch. A similar layer of absorbing material will be applied to the surface of the baseplate to make it nonreflective.

Since the reflector will have a solid, rather than a mesh, surface, no energy will penetrate the surface and produce backlobes.

Experimental results

A one-tenth scale model of the antenna verified that the desired sidelobe responses predicted by computed pattern simulations are attainable.

The model's reflector parabolic surface, with aperture dimensions of 2 ft width by

Fig. 6
One-tenth scale model verified low-sidelobe responses predicted by computer simulation. Operating frequency covers 31 GHz to 36 GHz. Test feed horns were designed to provide either horizontal or vertical linear polarization.

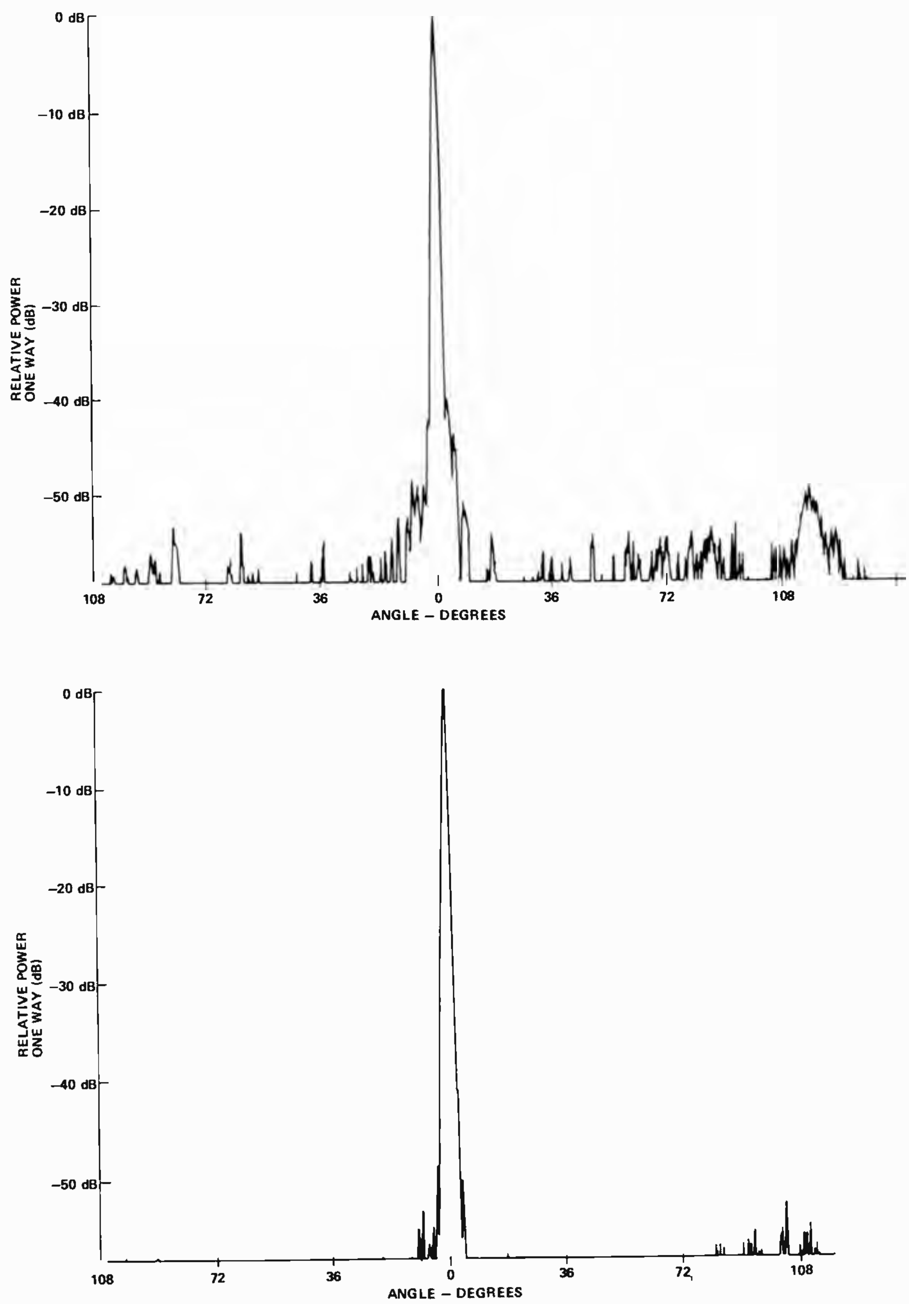

Fig. 7
Measured azimuth patterns of beam position number 4 at 33.5 GHz (top) and 36 GHz (scaled-up frequency taking model size into account) for the vertically polarized mode. These low sidelobes are typical of the key results of the development program, which verified that an antenna structure compatible with mobile, tactical environments can also be made to provide a high degree of immunity from ECM threats.

1.2 ft height, was machined from solid aluminum to a tolerance of better than 0.0015 in. rms. Fig. 6 shows the assembly of the scaled reflector, a five-horn segment of the feed group, and the absorptive shielding above and beneath the reflector, all mounted in test position.

An indoor anechoic test range was chosen as the pattern test site since it could measure antenna sidelobe responses reliably down to levels below −60 dB (this capability is difficult to obtain in most outdoor test ranges).

Fig. 7 shows vertically polarized azimuth patterns measured on the scale-model feed/reflector at two different operating frequencies, with peak near-in sidelobes below −40 dB diminishing rapidly to lower than −50 dB, in accordance with the design objectives. In general, wide-angle sidelobes are below −60 dB. These measured results correlate well with the computed pattern of beam No. 4 (shown in Fig. 5) in terms of maximum near-in sidelobe responses.

Fig. 8 shows how effective the absorptive shielding is in suppressing wide-angle elevation lobes in the zone of interest in relation to anti-radiation missiles. This pattern spans the angular region from directly overhead (at left) to vertically downward (at the right of the plot). The effectiveness of various widths of absorptive shielding at the top of the reflector is shown at the left, where upward radiation as a function of shield width is illustrated for widths equivalent to full-scale dimensions of 5 ft., 3 ft., and zero are overlaid. A nominal three-foot shield limits upward sidelobe radiation to less than −46 dB.

Implication/application of results

The overall result of this effort is an antenna design for tactical radar with: 1) wide instantaneous bandwidth (600 MHz at S-band); 2) low azimuthal sidelobes; 3) low sidelobes in a cone of 45° half-angle centered at the zenith (below −44 dB in a small region and below −50 dB elsewhere); 4) polarization diversity, including orthogonal, linear, and circular; 5) electronically steered beam over 20° in elevation compatible with one wide-bandwidth signal-processing channel.

This ECCM antenna demonstrates that, by applying design techniques specifically directed at sidelobe suppression, excellent sidelobe performance can be achieved with a reflector antenna. These techniques include: 1) much lower edge illumination than has been customary, at a modest sacrifice of aperture efficiency; 2) edge shielding to reduce the sidelobes caused by spillover at the edge of the reflector; 3) feed offset configurations that minimize blockage of the aperture by the feed structure; 4) shielding techniques that minimize high-angle radiation from the feedhorn structure.

This demonstrated capability shows the potential for the continued effective use of tactical radars of modest complexity and size—at modest cost—in an era of hostile environments for radar operations. And this potential, of course, implies even greater pressures on antenna designers in the future, to meet the inevitable demands of ever-growing sophistication and capability of ECM techniques.

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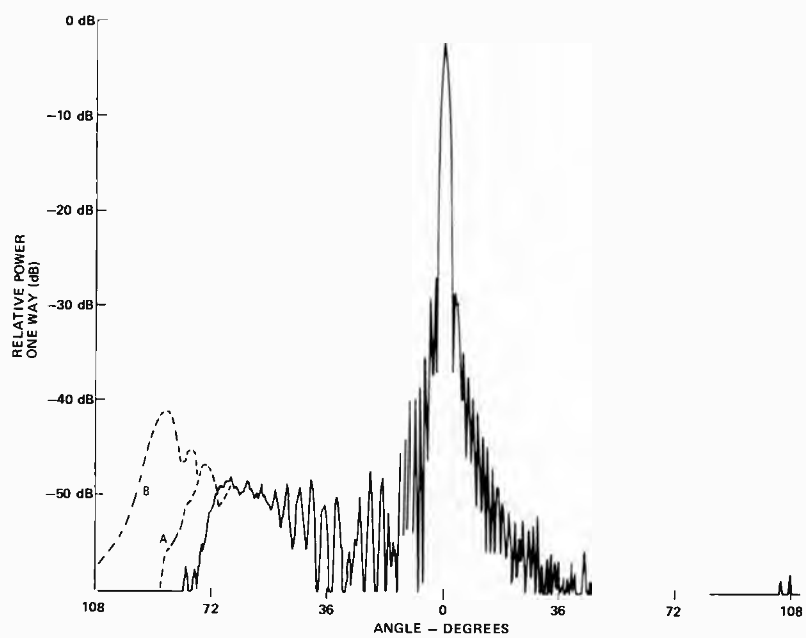

Fig. 8
Measured wide-angle elevation patterns of scale model. Strong spurious high-angle radiation increases the susceptibility of the radar to anti-radiation missiles. Most of this high-angle response is due to direct radiation propagating around the upper edge of the reflector from the feedhorn assembly. A moderate amount of shielding provides adequate suppression—dashed curves marked *A* and *B* show radiation pattern with small and no shield, respectively.

Bob Scudder has had approximately 30 years of professional experience at RCA in the design and development of antenna and microwave systems applicable to surface radars. This has included antennas associated with air-search and height-finding equipment, precision tracking radars, and phased-array antennas designed to support defense weapons systems.

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A short-range radar for measuring blast-furnace burden height

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J.P. Hoffman

Radar's high reliability, ability to operate continuously, and lack of mechanical parts can find work in unusual locations.

To improve the control of iron-producing blast furnaces, key furnace variables must be measured more accurately and reliably. One of these variables is the height of the burden (iron-ore/coke/limestone mixture) in the furnace. Each furnace has an optimum burden height determined by operating and design considerations. Deviating from this optimum height lowers efficiency and, in an extreme case, can cause furnace damage.

Problems with electromechanical systems

Presently, two electromechanical methods are commonly used to measure burden height.

They use: 1) a bar known as a stockrod or 2) a steel cable and heavy weight assembly. Both methods measure burden height by monitoring the distance that the rod or weight travels before contacting the burden surface. These electromechanical methods seem ideally suited for an environment as severe as the interior of a blast furnace, but production experience shows otherwise. With either method, burden height measurement is inaccurate if the equipment is not operating freely or if the rod or weight contacts a fluidized region of the burden and penetrates too deeply. Even more important, both systems have a record of frequent breakdowns. Thus, the main reason for developing an alternative method of measuring burden height was to improve measurement reliability.

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System requirements

Reliability, maintainability, and accuracy were the major system requirements.

RCA and Bethlehem Steel worked together at producing a new measurement system. At the outset of the program, they established the following system requirements:

high system reliability, to be gained by minimizing the use of mechanical components;

easy equipment serviceability, to be gained in particular by eliminating the need for components that are installed inside the furnace;

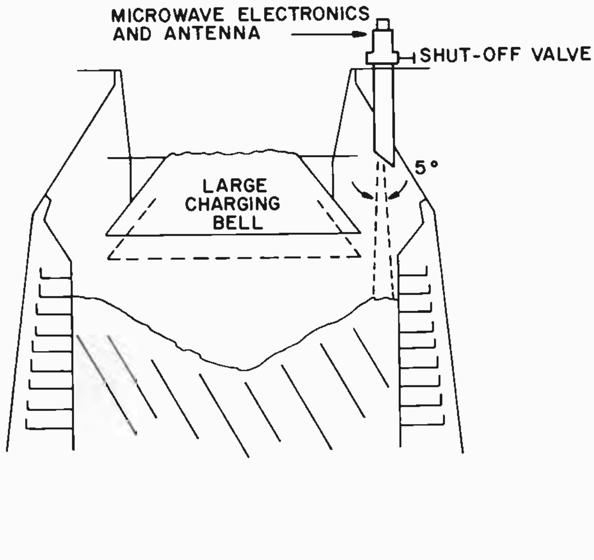

Fig. 1
Microwave measuring system, placed at the top of the blast furnace, avoids temperature extremes and problems with mechanical contacting systems. Blast-furnace burden (iron-ore/limestone/coke mixture) enters furnace through the top hopper, past charging bell and fills furnace as shown. Radar measures distance to burden surface within 6 inches.

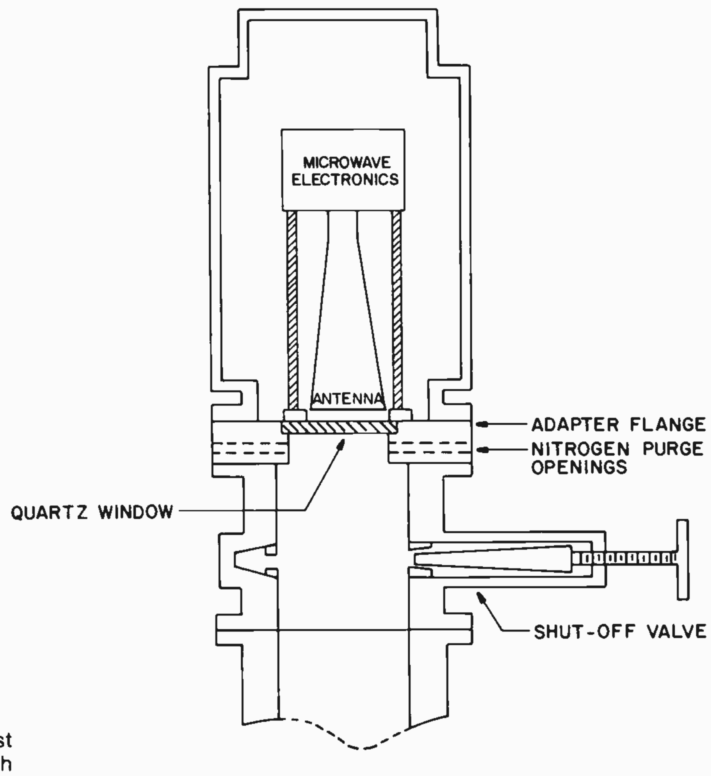

Fig. 2
Microwave instruments are external to the furnace and protected by the microwave-transparent quartz window and continuous nitrogen purge.

measurement accuracy of ±6 inches;

measurement range up to 35 feet from the furnace charging bell, as opposed to 15 feet or less for the conventional stockrods;

fully automatic operation; and

continuous operation (the mechanical stockrods must be raised above the charging bell while material is being dumped into the furnace).

These requirements led to a radar-based measuring system.

RCA and Bethlehem jointly developed a prototype measurement system; it was initially constructed and tested at RCA Laboratories in 1976 and then installed and evaluated on the "D" blast furnace at Bethlehem's Burns Harbor, Ind., plant. Initial startup problems were overcome and the equipment continues to be used for routine control of burden height. Based on the successful operation of the prototype, RCA developed two improved production systems, which were installed on the "C" blast furnace at Burns Harbor. They are currently being used in production to control furnace burden height. Design details of the production systems will now be described, in addition to results of the prototype evaluation program.

Mechanical equipment

The microwave instruments require a clean, dirt-free opening to the furnace interior and a protective enclosure for the microwave circuits.

The furnace had to be modified slightly for the microwave system. Fig. 1 is a simplified exposed view of the upper section of "C" blast furnace. Four stockrod pipes are located at 90° intervals around the conical section of the furnace exterior. One stockrod pipe houses a mechanical stockrod, the pipe located 180° from the mechanical rod is unused, and the remaining two pipes are used for the ranging radars.

While the furnace was down for a reline (a cleaning and resurfacing procedure done to the inside of the furnace approximately every five years), the following items, shown in Fig. 2, were added to the existing stockline indicator pipes:

a furnace shut-off gate valve;

an adapter flange with a quartz window;

provisions for purging the window with nitrogen gas; and

an enclosure to protect the microwave electronics and antenna.

The quartz window is transparent to microwaves and is required to pass microwave signals into the furnace interior. Nitrogen gas is introduced immediately below the window, through ports in the adapter flange, to prevent the buildup of carbon and iron dust deposits on the window.

Electronics

The electronic equipment consists of three basic subsystems;

1) *microwave electronics and antenna,* installed in a stainless steel enclosure on a rebuilt stockline indicator pipe;

2) *processing electronics,* also located on the furnace top and installed in a stainless steel enclosure; and

3) *display and computer interface electronics,* located in the furnace control room.

Fig. 3 shows the three electronic systems before installation.

The cw-fm (continuous-wave frequency-modulated system) determines burden range by measuring the instantaneous difference in frequency between the transmitted and received signals.

Fig. 4 illustrates the principle underlying the method of measuring burden height. As shown, a microwave oscillator is modulated in a manner that produces a swept transmission of frequencies. At some time, t_o, a frequency, f_1, is transmitted. This signal travels through the space in the furnace until it strikes the burden surface and is reflected back to the microwave electronics. This signal arrives at some time, t_1. However, now the transmitted signal has changed to a different frequency, f_2. The difference in frequency, f_b, between f_2 and f_1 is proportional to the range traversed by the signal and is given by:

$$f_b = 4R\, \Delta f\, f_m / c \qquad (1)$$

where

f_b = beat frequency or $|f_2 - f_1|$ (Hz)
R = range to the target (ft.)
Δf = swept frequency bandwidth (MHz)
f_m = modulation frequency (Hz)
c = 983.573 (ft.-MHz); speed of light

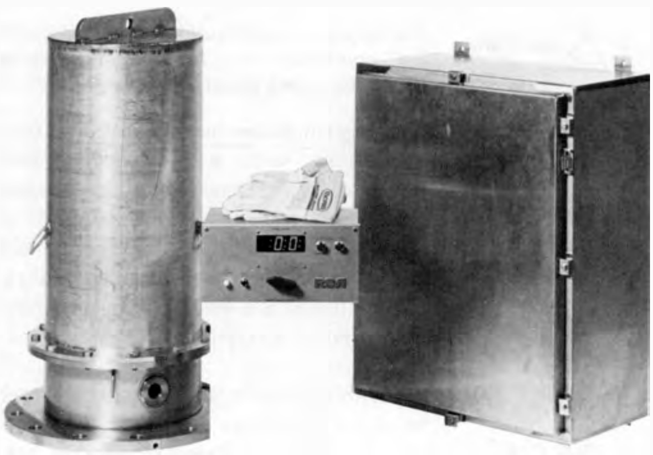

Fig. 3
System has three major components—microwave electronics/antenna enclosure (left) and signal-processing enclosure (right), which are installed on the furnace top, and display enclosure, which goes in furnace control room.

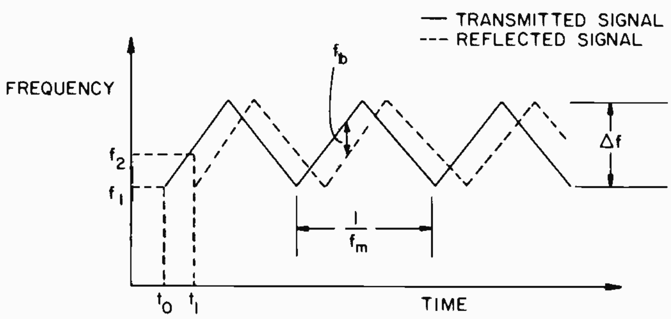

Fig. 4
Continuous-wave frequency-modulated system determines range by measuring the instantaneous difference in frequency between the transmitted and received signals. Because signal frequencies vary with time, frequency offset of reflected signal will depend on the time the reflected signal takes to return.

Fig. 5 is a block diagram of the microwave circuitry that generates and acquires the difference frequency signal. The modulated microwave signal is passed through a directional coupler and circulator and is transmitted to the burden surface through a 22-dB-gain waveguide horn antenna. A single antenna is used to both transmit and receive the signals. The mixer produces an output signal with a frequency, f_b, equal to the difference in frequency between the instantaneous transmitted and received signals.

Fig. 6 is a simplified block diagram of the entire radar system. All the electronics, including the microwave oscillator, employ high-reliability solid-state devices.

One difficulty often encountered in using high-accuracy, close-range radar systems is that any drift in the modulation parameters will produce an error in range.

To prevent such drift errors, calibration circuits, shown in Fig. 6, are incorporated into the production version. They are designed to maintain accurate range measurements regardless of modulation-parameter (f_m and Δf) drifts caused by component aging or temperature variations. These circuits operate as follows: a portion of the transmitted signal is directed through a separate coupler-mixer-circulator and sent down a coaxial delay line of fixed length that has been shorted at the far end. The signal is reflected at the shorted end of the cable and returns to the mixer, where it is combined with a portion of the transmitted signal. This produces a beat frequency determined by Δf and f_m. This "calibration" beat frequency is divided down digitally by the signal-processing circuits and used as a gate to count the target beat frequency. A change of the modulation parameters results in a corresponding change of both the calibration and the target beat frequencies. Since the change in the calibration beat frequency produces a corresponding change in the counter gate interval, the target frequency measured by the counter remains constant.

The calibration preamp includes a bandpass filter with 3-dB gain points at 94 and 109 kHz. The modulation parameters can therefore drift as much as 15% without affecting the measurement accuracy. The actual delay for the shorted coaxial line is 151.5 ns, which corresponds to a nominal frequency of 102 kHz.

The target preamp includes a bandpass filter with 3-dB gain points at 12.5 and 40 kHz. These frequencies correspond to a range between the large charging bell in its open position and a stockline of approximately 35 feet. The signal-processing circuits are shown schematically in Fig. 7. These circuits are contained in an enclosure that is also mounted on the "furnace top" next to the microwave components enclosure.

The target and calibration preamp outputs are connected to tuned-gain-response amplifiers in the electronics enclosure.

The target amplifier includes a 40-kHz low-pass filter with a 6-dB/octave gain response in the passband. This shaped response compensates for the fall-off in return-signal amplitude that occurs with increasing burden distance. The calibration amplifier is a 90-kHz high-pass filter with a flat gain response in the passband.

A portion of the amplified signal from each amplifier is used as a measure of return-signal amplitude. These signals are converted to a dc voltage and compared to preset threshold values by the signal-level detector circuits. The output of the calibration signal-level detector is used as an operational check for the system and the

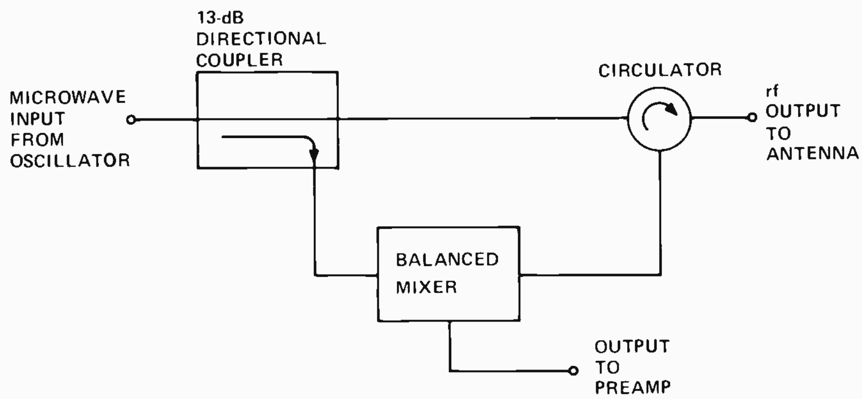

Fig. 5
Microwave circuitry sends and receives signals through same antenna, then produces frequency-difference output in mixer.

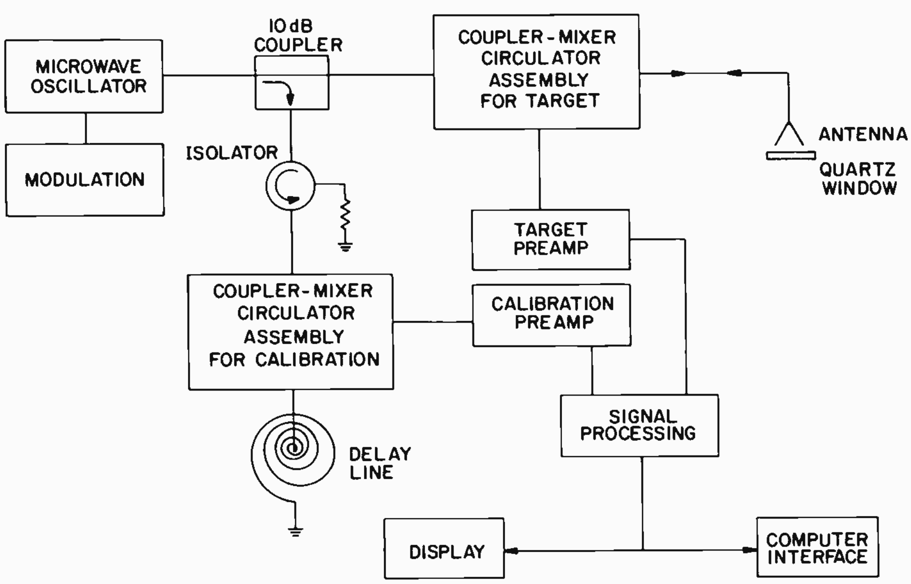

Fig. 6
Entire system incorporates microwave circuitry of Fig. 5, calibration circuitry to avoid problems with component drift, and separate signal-processing and display/interface electronics.

output of the target signal-level detector, which varies considerably during normal operation, is used as a squelch.

The target and calibration amplifiers connect to target and calibration phase-locked loops (PLL). The calibration PLL is a single loop with a long time constant to track the slowly varying calibration frequency. The target PLL has two series-wired loops with shorter time constants.

The output of the calibration PLL and the target PLL are connected to the divider-counter circuit. The target frequency is divided by three and counted over a gate time interval determined by the calibration frequency. The calibration frequency is divided by an adjustable constant ranging between 41160 and 49096. This produces a gating rate between 1.9 and 2.7 Hz, depending on the modulation parameters. The total number of target pulses counted in this gate interval is equal to 100 times the range in feet from the microwave receiver to the burden surface.

The three most significant digits are transmitted in BCD format to the control-room display.

Although these BCD digits represent the range in feet from the microwave receiver to the burden surface, the furnace operator generally is interested in knowing the distance in feet from the large bell in its closed position to the burden surface. This distance reading is developed in the display enclosure by digitally subtracting a user-specified fixed distance from the total range distance. This offset distance is determined by the furnace geometry and normally is between 15 and 25 feet.

The display enclosure also contains a stockline command circuit, which compares a user-selected burden level with the measured level. When the burden level falls below the user-selected level, the command circuit sends the furnace computer a signal requesting that more burden materials be added to the furnace. The furnace operator may select burden levels between 5 and 10 feet in steps of one foot.

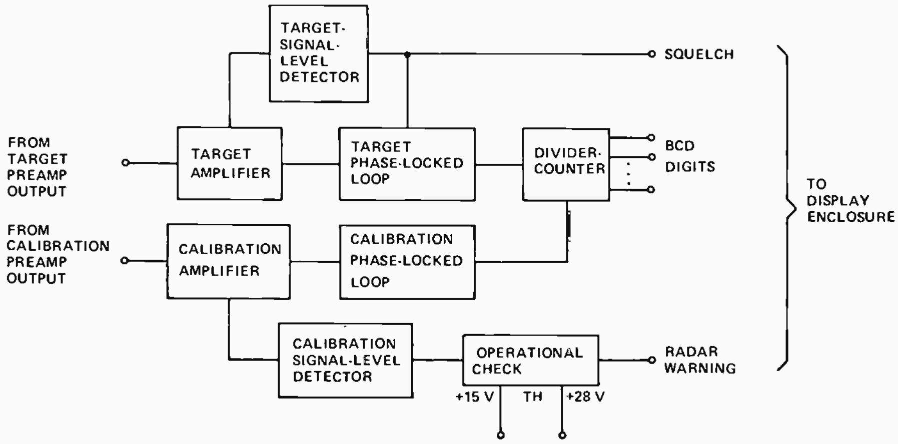

Fig. 7
Signal-processing circuits are also mounted at furnace top. Calibration works by automatically scaling the indicated target range by the ratio of the true to indicated delay line range. Target preamp is tuned to compensate for lower returned-signal amplitude at greater measuring distance.

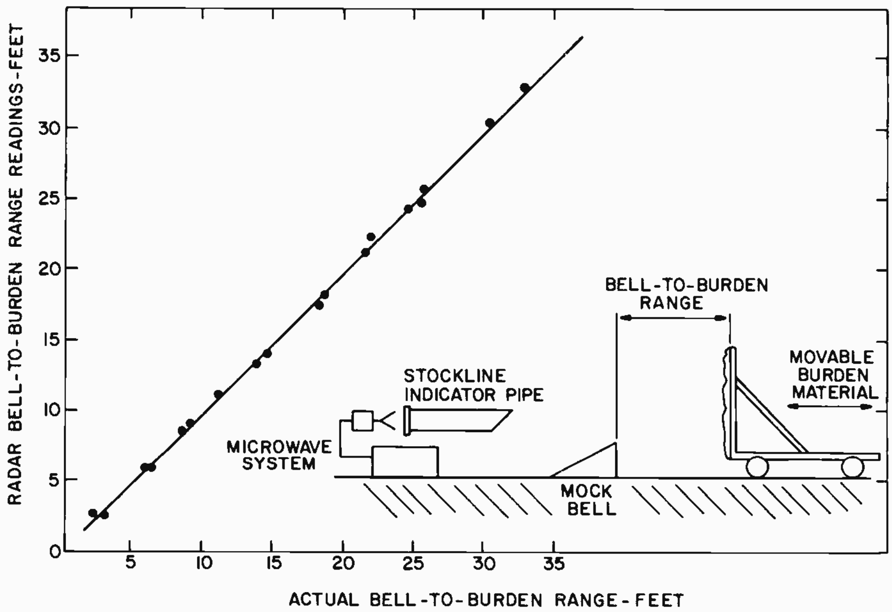

Fig. 8
Experimental setup showed that microwave system worked within the desired 6-in. accuracy over the 35-ft. range.

Evaluation of the prototype system

The six-inch accuracy goal was met, and the units have operated reliably so far.

Following construction, temperature and measurement-accuracy tests were conducted on the prototype system at RCA Laboratories before shipping the equipment to the Burns Harbor plant. Measurement accuracy was determined by constructing a horizontal target range to simulate the physical geometry inside the furnace. Fig. 8 shows this experimental setup together with test results. For these trials, a pipe of the same size and shape as the furnace stockline indicator guide-pipe was modified to accept the quartz window. Sheet metal, placed approximately 16 feet from the antenna, simulated the large charging bell. Samples of burden were attached to a movable 6-foot-square vertical surface. The trials conducted with this setup showed that the microwave distance measurements agreed with the actual distances to within the desired 6-in. accuracy over a range up to 35 feet from the bell. For the temperature trials, the range readout was monitored while equipment temperatures were varied from −20 to +140° F, which is the expected range for the externally mounted radar unit. The variations in range readings, at a range of 30 feet from the bell, were less than 3 inches over the entire temperature range.

Following the trials at RCA, the equipment was installed on the Burns Harbor "D" blast furnace. After initial equipment debugging, the equipment was calibrated and production evaluation was conducted. Although a rigorous determination of burden-height measurement accuracy was not possible, because there was no accurate independent reference in the furnace, a practical estimate of the accuracy was obtained by comparing the microwave measurements with mechanical stockline measurements averaged over many charging cycles and under various furnace operating conditions. Fig. 9 shows typical results obtained from the mechanical indicator and the microwave equipment during eight consecutive burden charges. The first three recordings show rapid burden movement, while the remaining five show slower movement. On the fifth recording, a small burden "slip" of approximately one foot in height occurred. Based on the data from the experimental trials at RCA and the analysis of operating data of the type shown in Fig. 9, we judge that the equipment indicates burden height within approximately 6 inches of actual burden height.

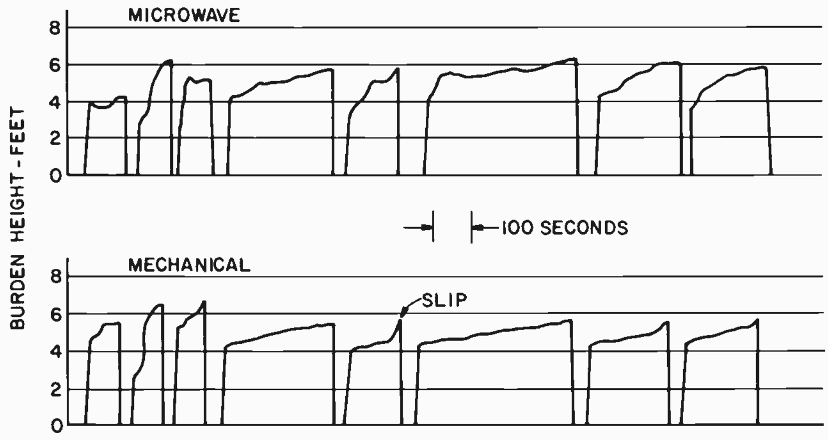

Fig. 9
Comparison of microwave and mechanical systems used in same furnace shows good agreement. Burden height is taken as the distance from the large charging bell to the burden surface. Burden "slipped" in fifth trial shown here.

Acknowledgments

Grateful acknowledgment is given to L.M. Zappulla, E. Mykietyn and J.E. Brown of RCA Laboratories and to G.R. Crossley, W.E. Swan and T. Koselke of Bethlehem Steel for their many constructive contributions to this effort.

Bob Paglione has ten years of experience in the microwave field. He is now working with rf and microwave equipment for heating biological materials. Besides designing numerous microwave components, he has also developed a computer-controlled variable mismatch used in designing solid-state microwave amplifiers.

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Henry Johnson has 19 years of experience with the Microwave Technology Center. His recent work has centered on commercial radar applications—besides the blast-furnace radar project described here, he has also worked on collision-avoidance radars and a microwave speed sensor for locomotives.

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John Hoffman has a background in electrical engineering and 17 years of experience with Bethlehem Steel's Research Department. His recent work has centered on the development of instrumentation for blast-furnace applications. Examples include the development of infrared imaging equipment to measure temperature distributions, tests involving the use of neutron gages to measure coke moisture, and participation in the development of the microwave equipment described here.

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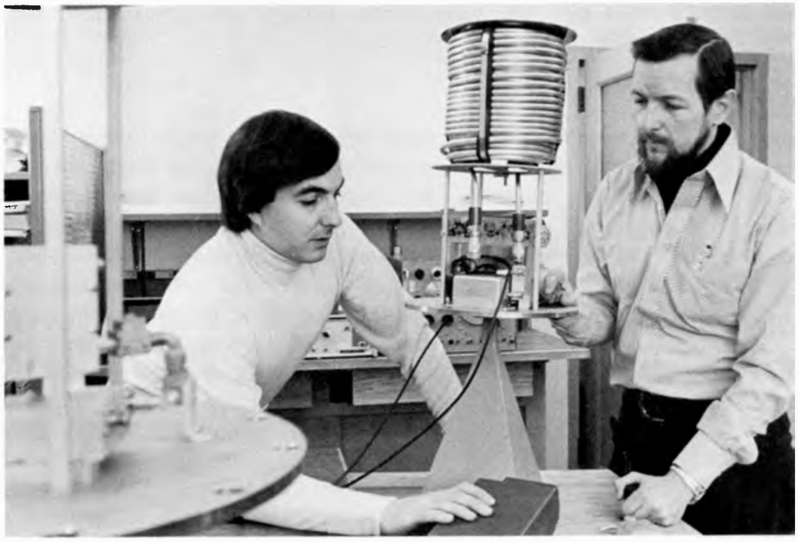
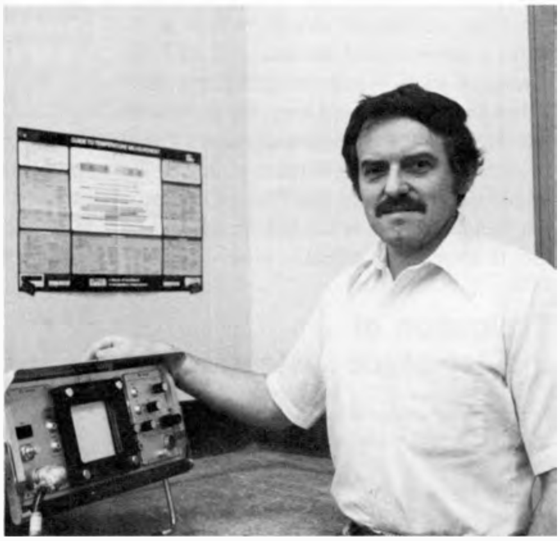
Authors Paglione (left) and Johnson with the microwave electronics and antenna subsystem for the blast-furnace radar. Coil of coaxial cable at top is for calibration, rf/transmitter electronics are at center, and transmit/receive antenna is at bottom.





Microcomputers for radar systems

Radar designers are using microcomputers to distribute computer-processing load throughout their systems for lower cost, improved thruput, greater versatility, and easier system development.

B.D. Buch | S.L. Clapper | R.J. Smith

General-purpose digital computers have been used to control multifunction radars for the past ten years, but not without problems. In particular, the need for extensive software development and its control have been very costly. One alternative is to develop special-purpose hardware; however, this alternative is also costly with the additional drawback of inflexibility. Microprocessors offer a third alternative.

Special-purpose programmable microprocessors have already been used in radar for such functions as coordinate conversion. Antenna-array beam steering and tracking also have been prime candidates for microprocessor-based implementation. Removing such functions from the general-purpose computer and distributing them promises several benefits:

- *Lower cost*—a smaller general-purpose computer can be used. Removing well-defined computational functions permits more computer resource for control and decision processing. This also implies the use of higher-level command languages in the general-purpose computer for reduced software cost.
- *Higher traffic rates*—total processing capability is increased by adding more special-purpose processors.
- *Expandability*—the system can be upgraded to higher traffic rates by adding more special-purpose processors.
- *Software/firmware management*—the system partitioning forced by distributing the processors reduces the size of the large re-entrant program resident in the general-purpose processor. Each special-purpose processor is identified as a radar function, and design review techniques for firmware similar to those for hardware can be instituted.

Although a distributed processing approach solves some of the problems associated with controlling a radar by a general-purpose computer, new problem areas arise because a gap exists between the microprocessor as an LSI chip and its actual realization as hardware and firmware in a system. LSI microprocessors represent complex subsystems, but they require supporting hardware and software to become microprocessor-based systems.

In considering a microprocessor* for a particular application, several factors must be evaluated:

- *Speed*—Is the microprocessor fast enough for the application?
- *Word size*—Does the microprocessor have the required precision?
- *Architecture*—How is the microprocessor system best configured for the application?
- *Interface*—How is the processor interfaced with other system components (memories, control registers, busses, etc.)?
- *Packaging*—How can the microprocessor system functions be packaged to be consistent with existing packaging systems yet be flexible enough for future systems?
- *Programming*—Does sufficient support exist so that the microprocessor system programming can be performed?

*The terms microcomputer and microprocessor are often used interchangeably, yet there are important differences in their meanings. A microprocessor is the small central processing unit (CPU) that performs the logic operations in a microcomputer system. In the microprocessor or CPU, instructions are decoded, arithmetic and logic operations are performed, and timing signals are generated. However, much more hardware—such as memory, a clock, and interface circuits—may be necessary for full-scale "computing." This additional hardware, in conjunction with the microprocessor, is called a microcomputer.

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MSR's approach to distributed processing

Recent efforts at MSR have addressed the development of the operational elements (hardware and software) required for distributed processing in radars.[1] The first step in this development is the selection of a microprocessor family; the second step is partitioning the designs into functional modules that can be used with each other in different ways so that a given requirement can be met with a microcomputer matched to that need.

The questions of speed, word size and interface have been considered versus the application requirements, and the hardware approach developed is based on bit-slice functional modularity. We use a bit-slice bipolar microprocessor (Advanced Micro Devices, Type 2901) for speed, and other functional modules (RAM, PROM, bus interface, etc.) which can be interfaced and configured for word size in a variety of processing architectures as a function of the application.

Six functional modules have been identified and implemented.

The *microprocessor* module uses four AMD type 2901's in a 16-bit microprocessor module. The module is designed to be a 16-bit slice so that a 32-bit processor can also be configured. The module uses seven other LSTTL (Low power Schottky TTL) MSI/SSI devices and dissipates approximately 4.0 W of power.

The *microprogram PROM* module is a 512 word × 40 bit PROM (programmable read-only memory) to hold microprograms. It consists of 17 bipolar devices and dissipates approximately 4.3 W of power.

[1] Buch, B.D.; Clapper, S.L.; Smith, R.L.; "Bit-slice module set for microcomputing"—*private correspondence*.

The *macroprogram PROM* module is a 2k word × 16 bit PROM used to hold the macro-level program. It consists of 10 bipolar devices and dissipates approximately 5.1 watts of power.

The *RAM* module is a 1k word × 16 bit RAM (random-access memory). It uses 16 CMOS/SOS RAMs for optimum speed/power tradeoff and three bipolar devices (19 devices total). The typical power dissipation is estimated at 0.2 W.

The *bus interface* module contains tri-state registers and drivers and is used to "hold" the various system configurations together. It consists of 14 LSTTL devices and dissipates approximately 1.0W.

The goal is to incorporate high-density state-of-the-art packaging techniques with no loss of generality.

This goal was met by implementing the functional modules on 3.8 × 1.78-in. ceramic substrates with active devices enclosed in leadless hermetic packages.

The large packages in Fig. 1 are the leadless carriers holding the 2901 microprocessors. The smaller packages are the MSI/SSI devices. Each module is implemented as a large 72-pin (36 pins/side) dual-in-line package and is made to be mounted on standard 0.3-in. centers. This type of module can be used on either a printed-circuit board or wire-wrap board.

Software/firmware development

Since the hardware module set is subject to change as new devices are introduced, the main challenge is to produce firmware that does not become obsolete as the hardware changes. This has been accomplished through the development of "architecture independent" support software used in conjunction with a PDP 11/03-based microcomputer development system. Program development using the actual hardware is accomplished by using macro-ROM and micro-ROM simulator modules as shown in Fig. 2. These modules are loaded from the PDP 11/03 microcomputer but are functionally and mechanically identical to the micro-ROM and macro-ROM modules used in an actual application. The difference between the simulator modules and actual modules is speed. The simulator modules are slower since an instruction decode requires that control bits be obtained from the floppy disk.

Another approach to program development is to use a simulator. Simulators for 16- and 32-bit microcomputer systems have been developed to run on any PDP 11 minicomputer.

Microcomputer system

Although the hardware modules developed at MSR allow for architectural variations, many applications in radar systems can be satisfied using a standard processing architecture. The 16-bit microcomputer of Fig. 3 represents a general-purpose architecture that can be tailored to a specific application by using microcode and/or by adding special purpose processing hardware (e.g., multipliers). A 16-bit microcomputer with 2k words of macroprogram and 1k words of data RAM requires 12 modules total. The architecture can be extended to form a 32-bit microcomputer by adding more modules. A 32-bit microcomputer with the 2k words of macroprogram PROM and RAM may be added if required. The microcycle time of this 16/32 bit microcomputer is 250 ns with a typical register-to-register add time of 500 ns at the macro (assembly language) level. Provision has been made for microprogrammed two's complement multiply and divide. The 16-bit multiply requires 19 microcycles or 4.75 μs and the 16-bit divide requires 29 microcycles or 7.25 μs.

Although the microcomputer has been designed so that it can be tailored for a particular application using microcode, a general-purpose assembly-level instruction set has been implemented for branching, memory/ memory moves, and memory/register moves. These instructions are modeled (not exact emulation) after the PDP-11 instruction set; actually, they form a subset of the PDP 11 instruction set and use the same assembler mnemonics so that a source program can be written on a PDP 11 and run on the microcomputer.

Richard Smith has 15 years experience in design and development of radar signal processing architectures. He was responsible for development of microprocessor-based radar applications for beam-steering control, tracking, coordinate conversion, and servo loops.
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Bruce Buch has contributed to design and development of special purpose microcomputer systems since 1975. He is presently engaged in developing signal and multiprocessor architectures for beam-steering control of phase array radars.
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Ext. PM-3587

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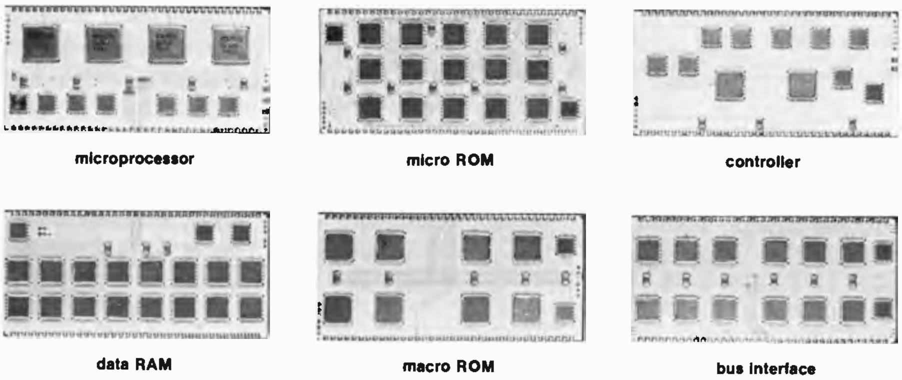


Fig. 1
Functional microcomputer modules. This approach permits use of advanced packaging technology to incorporate high density packaging without loss of generality.

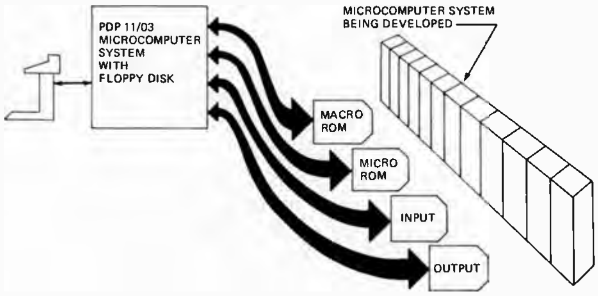


Fig. 2
Microcomputer development system. This system uses standard I/O ports to create a test bed for performing macro- and micro-level programming for the basic module architectures.

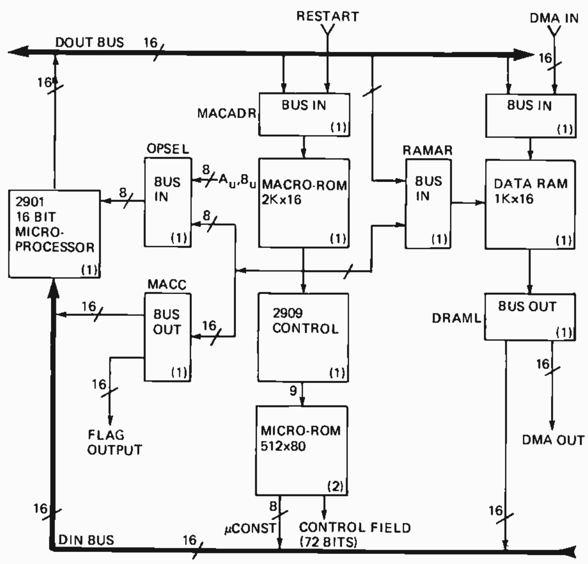


Fig. 3
Basic microcomputer architecture. This drawing shows the module types and quantities needed (in parenthesis) to implement a 16-bit microcomputer. Note that the modules labeled BUS IN and BUS OUT are actually one module type, the BUS INTERFACE module. The major functions in the 16-bit microcomputer are: 2901 16-bit microprocessor (CPU function); an operand select function (OPSEL) used to select 2901 register file addresses from either micro or macro program; a macroprogram address register (MACADR); a MACRO-ROM module for macroprograms; a 2909 control register (RAMAR) and DATA RAM module; two holding register/driver modules (DRAML) for RAM data (also DMA input/output); and a register/driver module for transferring 16-bit constants from the macroprogram ROM to the 2901 input (MACC).

Modular firmware concept

The basic microcomputer of Fig. 3 is the focal point for using hardware modules as a building block to construct "computer-like" hardware designs. A similar concept applies to the firmware.

Many radar algorithms are common to many radar systems. If these common algorithms can be identified and microprogrammed, elements of a radar-processing language can be evolved. The firmware concept entails development of many special-purpose microprograms found in radar systems, so that the system designer can select those microprograms useful to his application. Once PROMs are burned in, he then essentially has a special-purpose computer for his unique application.

Applications

Several radar functions have been identified for microcomputer implementation. As summarized in Table I, these fall into three categories: off-loading main computers by processing well-defined functions in special purpose microprocessor systems; replacing functions now performed in a minicomputer where the general-purpose nature of a minicomputer has more processing power (and cost) than required; and hardware reduction by using microprocessors to perform functions traditionally done with hardware. A few specific examples are described below.

Coordinate conversion can be performed in less than 3 ms using a microcomputer.

A basic computational task in a radar system where the antenna is located on a moving platform is to convert the variable platform coordinates to a fixed reference coordinate system. This task can be delegated to one of the system computers. Since the coordinate conversion must be updated at frequent intervals (i.e., 5 ms) and the computations involve generating sines and cosines, considerable CPU time is consumed. Furthermore, operation with large word size (i.e., > 20 bits) is required. If this task can be removed from the central computer and done with a bit-slice microprocessor, the central computer loading can be reduced significantly.

In the coordinate conversion process, a matrix based on the variable platform coordinates must be multiplied with a reference matrix. Fig. 4 shows the typical

Table I
Microprocessor application to various radar system functions.

Application	*Function*
Off-loading main computers	Coordinate conversion Track functions Radar return processing Command output processing
Minicomputer replacement	Displays Checkout and monitoring Servo computers Fire control computers
Hardware reduction	Beam steering controller Post processing (monopulse, interpolation, etc.) Input/output buffer to signal processor Data formatting (asynchronous data collection) Data bus controllers ("smart" busses)

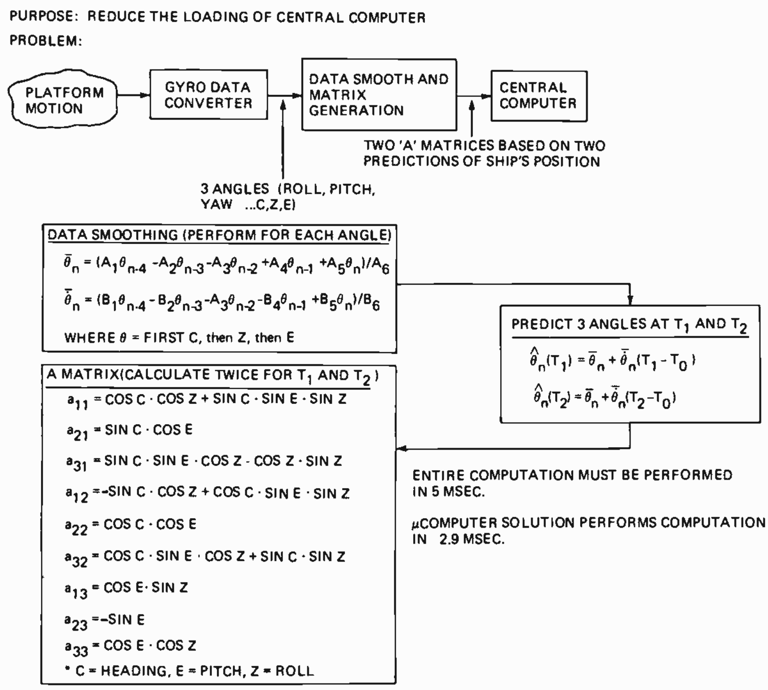


Fig. 4
Coordinate conversion problem. Variable motion of the antenna's platform must be converted to fixed reference coordinates and updated every 5 ms.

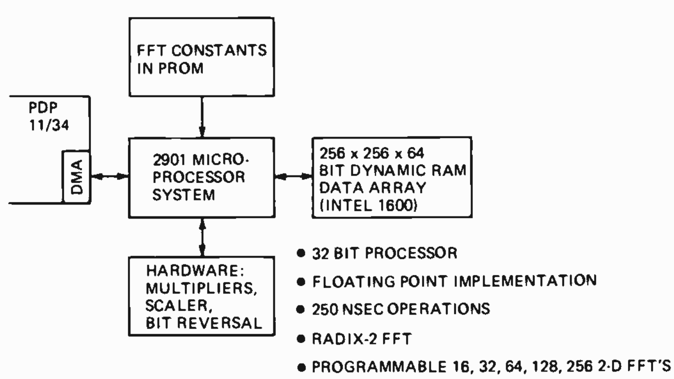


Fig. 5
Two-dimensional fast Fourier transform performed via microprocessor.

calculations required. Three position angles (roll, pitch, yaw) are digitized, then smoothed using a polynomial filter. The rate of change for each angle is also determined so that the platform position can be predicted at some future time (T_1 and T_2). The predicted position angles are used to calculate two 'A' matrices. These two matrices are then multiplied with the reference-coordinate matrix.

A bit-slice microprocessor system has been used for this type of coordinate conversion process in the AEGIS Air Defense System. This processor represents an early bit-slice design—a 24-bit implementation using standard AEGIS modules. The microprocessor is the AMD 2901 and has a 380-ns clock time. This allows computation of a 24-bit sine in 98 μs. This processor represents a significant off-loading of one of the AN/UYK-7 system computers.

Data Formatting Unit (DFU) is another bit-slice microprocessor implementation in AEGIS.

The Data Formatting Unit processes the interfacing data between the ship's data sensors and the command computers. The function of this processor is to gather asynchronous data (e.g., 1, 2, and 3 bits at a time) from the various ship sensors, place the data into standard formats (e.g., 16- or 24-bit words), and , upon command, transfer the formatted data to the central command and decision computer. This processor is the same basic AMD 2901 implementation as the AEGIS coordinate converter.

Microprocessors are being used to speed up the two-dimensional fast Fourier transform for antenna pattern measurements.

Testing and analysis of phased array antennas requires far-field pattern measurement. One technique for doing this is to take near-field measurements and transform these near-field samples to far-field patterns using a two dimensional (2-D) fast Fourier transform (FFT). In testing the phased array, a large amount of data is collected and the requirement exists for many 2-D FFT computations. This requires considerable computer processing, and results in a long delay between measured data and processed data used for analysis. One approach to reducing this time is the implementation of a bit-slice microprocessor system, microprogrammed to perform the FFT algorithm. This FFT processor is used in conjunction with a minicomputer (PDP 11) as shown in Fig. 5.

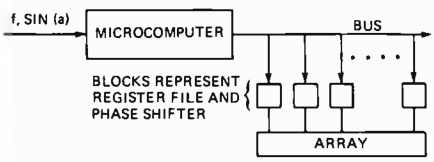
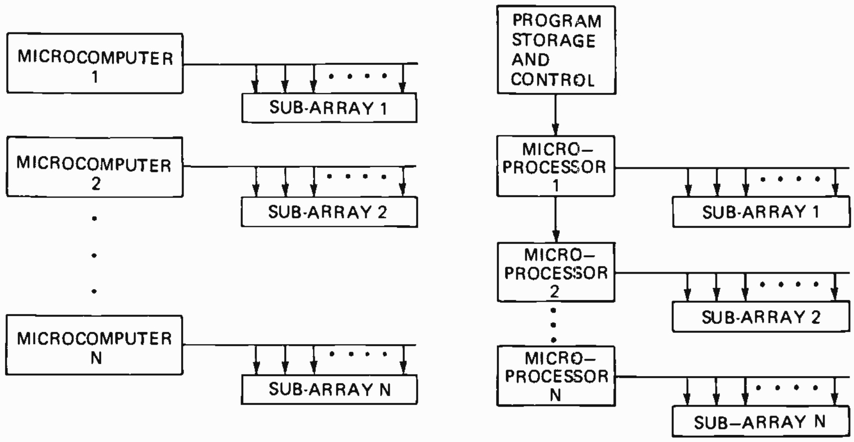


Fig. 6
Phased-array-antenna beam steering via microcomputer.



a. **Multicomputer** beam steering control.

b. **Multiprocessor** beam steering control.

Fig. 7
New beam positions can be computed more rapidly if the array is partitioned for separate loading.

Since the processing is two dimensional, a large random access memory is required. Furthermore, special-purpose hardware such as TRW's 16×16-bit multiplier is employed to speed up the radix-2 FFT calculations. Communication between the FFT processor and PDP 11 computer is via a direct memory access (DMA) channel. This application is a good example of how the basic microcomputer of Fig. 3 can be tailored with special-purpose hardware and microprogramming to implement a very specific hardware function.

An approach for microprocessor steering of a phased array has been developed and proposed for future shipboard systems.

The technique used incorporates a "read 'A' - while write 'B' " type register file at each phase shifter. This enables the array to use the phase words for transmit and receive during radar dwell period N while the bit-slice microprocessor microcomputer is loading the phase words for dwell period $N+1$.

Since the loading of the phase-shifter storage elements is done sequentially, the microcomputer can interface to the phase shifter through a single bus for data, phase-shifter address, and control as shown in Fig. 6. The dwell time or time to compute new beam positions can be speeded up by partitioning the array into subarrays and using a microcomputer to load each subarray in Fig. 7a. This approach, however, is wasteful because of the redundancy of having many microcomputers executing the same routine. The redundancy occurs in program storage hardware and can be eliminated by using a multi-processor microcomputer. The multiple microprocessors execute a single instruction stream using constants which correspond to a particular subarray. This architecture is shown in Fig. 7b. This approach to beam-steering control, along with the hybrid packaging technology will result in a physically small beam-steering controller that can be located near the antenna. This will reduce the cabling required to interface the beam-steering controller to the array.

The beam-steering controller is yet another example of how the module types described earlier can be used to implement different computing architectures.

Another proposed microprocessor application is checkout and monitoring.

This approach is based on distributing microprocessor checkout-and-monitoring (CAM) systems based on functional and cabinet-level partitioning. Each microprocessor CAM (μCAM) is tied into hardware test- and data-monitoring points. The μCAMs sequence through test routines that query the individual hardware points and format the data for block transfers to the central processor. The central data processor manages the distributed μCAM system on a functional basis.

Faults are detected at the subsystem level through continuous monitoring by each μCAM. When a fault occurs, the μCAM senses this and notifies the central data processor via interrupt. The central data processor then queries the μCAM to determine the nature and seriousness of the fault. Any further diagnostics or fault isolation routines are then directed by the central data processor. Each μCAM will contain "canned" diagnostics for fault isolation at the least-replaceable-unit level of hardware and will report the failed hardware unit location back to the central data processor.

This approach to checkout and monitoring eliminates the large data base requirements of a central computer approach since the data required for fault detection and isolation (test-bit patterns) are distributed throughout the hardware.

Conclusions

The microprocessor in a radar system is a component to be sold as a part of a larger product, and can be used to implement those functions which are more or less common to all radars. The microprocessor as a device is not particularly significant in these applications; however, the microprocessor as a system function is. The impact of the microprocessor in radar systems is related to the degree to which it remains a flexible device that can be used for multiple functions.

The key issues, therefore, in applying microprocessors to radar systems, are not the device itself but the software and firmware required to make it into a radar subsystem component. The questions to be resolved are ones dealing with system architectures and firmware development. The modular approach to hardware and firmware described here is directed towards microprocessor use in that context.

Programmable processors and radar signal processing—an applications overview

M.G. Herold
M.C. Timken

Developers of programmable signal processors are continually attempting to outreach each other with greater throughput or programming ease, or both.

Marty Herold has been involved with the design of signal-processing systems since joining RCA in 1957. His experience includes analog computing, servos, frequency synthesis, receivers and digital circuit and system design. Since 1970 his primary assignments have involved systems design of real-time programmable signal processors for communications and radar applications. He is currently the systems engineer responsible for design and delivery of a programmable, real-time, digital communication receiver.

Maurice Timken joined MSR in 1957. He has extensive background in signal processing techniques and has designed and developed these subsystems for application to radar systems such as TRADEX, BMEWS, ASFIR, and AN/FPS-95. In his present assignment as a unit manager in the System Engineering Department, he is responsible for development of a programmable signal processor for communications application.

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Authors **Marty Herold** (left) and **Maurice Timken** with an SPS-81 Programmable Signal Processor in the background.

In radar, signal-processing functions are performed on received signals so that desired target returns are enhanced and noise, clutter, and other extraneous signals are de-emphasized.* In early radars, signal processing was an analog-circuit function; later came hardwired digital logic circuits; the more recent trend is toward programmable methods.

Today's radars place wide-bandwidth high-speed demands on the signal processors; these processors must also be adaptable to changing needs. Thus, speed and flexibility establish the architectural tradeoffs for selecting the best signal processor. Speed can be achieved in a variety of ways, principally by means of performing functions simultaneously or in parallel; flexibility is achieved by software.

At one extreme of the tradeoff is the hardwired approach—maximum speed, little flexibility; at the other extreme is the general-purpose computer—a lot of programming flexibility with high-level languages, but orders of magnitude below the speed required for radar processing. Programmable processors fall in a wide region between these two extremes, approaching one or the other limit, depending on the degree of parallelism in the architecture and hence the complexity in programming. No clear criteria can be set forth to identify an optimum level of flexibility (programmability) and speed (parallelism). The system design goals involved, however, are quite clear: maximum throughput, with optimum use of available resources, and without an overcomplicated program.

* Walt Weinstock describes the radar signal-processing function in some depth elsewhere in the issue.

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What's a programmable signal processor?

All programmable signal processors are "standalone" units controlled from a host minicomputer. The software package in the host minicomputer provides program assembly, control, and debugging capability. Programs for signal-processor operation can be stored on disk or tape and loaded under control of the host minicomputer. Therefore, all peripherals available to a computer (teletype, CRT terminal, printers, disk operating systems, magnetic tapes, etc.) can be integrated into a signal-processing module through the host minicomputer.

Programmable processors are usually delivered with a software library package providing such functions as array multiply, add, subtract, and combinations thereof, plus more complex functions such as complex multiply, FFT (fast Fourier transform), recursive filter, and power spectral density. The sophisticated user can add functions of his own to the library. The attractiveness of the array library software is that it provides a means of quickly applying a programmable processor to a computation problem, since the functions are Fortran-callable.

The major drawback to use of array library software for real-time signal-processing is the efficiency lost in overhead. That is, each library function called requires the computer to perform extra operations (use extra memory and time) needed to link these various "canned" programs at the processor level. For real-time signal-processing applications such as radar, the processor must be programmed in microcode to achieve the desired throughput. Programming at the microcode level, called microprogramming, requires that the user develop instructions practically at the logic design level.

What happens in the real world?

Consider a typical situation that might employ a programmable signal processor. The usual case is a multiplicity of baseband signal processing computations that would otherwise require many dedicated digital processors. For instance, a typical radar may require FFT, doppler filtering, range and monopulse angle estimation, interpolation, etc. If a programmable processor is fast enough to perform all of these functions, we have a prime application candidate. (The programmable processor is misused if dedicated to a single heavy-load function such as complex translation and filtering for preprocessing—the sample rates alone could take all the resources of the processor and you're not able to use its programmability.)

Two considerations are of prime importance when designing a programmable processor into a system:

- Partitioning of processing function for efficient "overlay" management.
- Efficient flow of input and output data.

The functional partitioning of processing functions into overlays (smaller program segments) is necessary since programmable processors have relatively small program memories and thus cannot hold the total signal-processing repertoire. The program overlays are generally kept in large bulk memories, easily accessible to the processor. These program segments are then called and placed in program memory only when the functions they perform are needed in real time.

The dynamic swapping of program segments in program memory imposes the further requirement for sequential batch-mode processing of data queued up into blocks. This mode requires the completion of each processing program segment (on all data) before proceeding to the next signal segment. Such a characteristic leads to memory size tradeoffs to reduce the overhead associated with program swapping.

The input/output flow of data and accompanying control strategies must be coordinated. Some processors cannot reach out and obtain data. Instead, blocks of data and/or control must be moved into a processor memory before processing can begin. Output is the reverse process. In most cases, processors must be stopped for external program changes by the host CPU. If uninterrupted continuous processing is necessary in real-time control situations (e.g., operator inputs to add or subtract processing functions or change parameters), an indirect means of control is needed.

Because these processors operate independently of the host minicomputer, and because control is exercised indirectly via a control program in the mini's memory, an executive control program must be designed into the software system of the processor itself. These control programs can range from very rudimentary instructions to high-level control programs. The form of control advocated here is a control program residing in the signal processor which can fetch control statements from the host minicomputer's memory, interpret the requirement, and send to the proper control subroutine that part of the control program required to accomplish the intent of the control instruction.

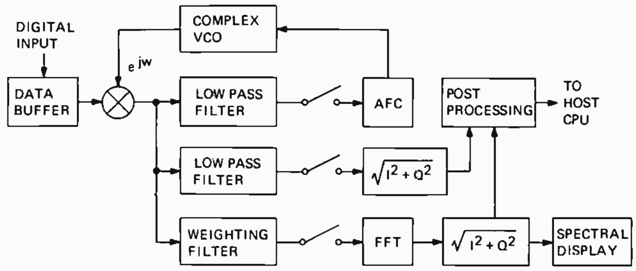

Fig. 1
Typical processing scenario. Hypothetical multiple-function radar processing involving time, frequency, and display processing.

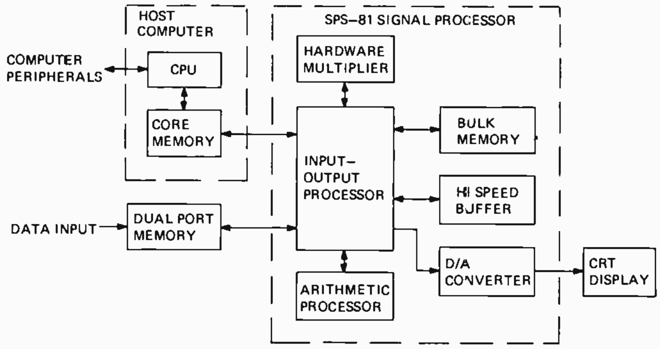

Fig. 2
Signal-processing system. A typical application architecture involving host computer control, display, and data/signal processing flow from input to computational output deposited in the host computer memory.

A typical problem

Consider the typical processing segment shown in Fig. 1. The process shown involves an AFC loop for doppler extraction, with complex translation to baseband. The baseband signal envelope is detected for various post-processing uses while the input spectrum is analyzed in parallel for display and other automatic, spectrum-dependent post-processing functions.

Assume a typical programmable processor such as the SPS-81 (SPS, Inc.) which has a system architecture as shown in Fig. 2. This system provides a natural partitioning of functions. A dual-port memory is provided: one port buffers input data from an external processor; the second port is used by the processor to fetch data independently. The SPS-81 has a bulk memory to store program overlays, a high-speed buffer for scratch-pad and interim storage, a hardware (hard-wired) multiplier, and a DMA (direct memory access) interface to deposit results directly in host minicomputer's memory. Results can also be output via the D/A converter for display.

By functional partitioning, we match the process to be computed with the internal processor.

Filtering, AFC feedback, complex translation, FFT, and envelope detection are performed in the arithmetic section. All of these processes involve various combinations of multiplies and adds for which the arithmetic processor is designed. Post processing, which generally involves searching, thresholding and branching (i.e., single-thread processing) is performed by the input-output processor, which is, in fact, a highly efficient microprocessor. The hardware multiplier speeds computations and avoids the need to commit the arithmetic section (and its setup overhead) to randomly programmed, single multiplications.

Functional partitioning of the coding for the arithmetic processor depends very much on the small program memory of the arithmetic section. For example, a microcoded instruction for the arithmetic section has 96 bits per word, but only 16 instructions can be stored at once. The index section, which drives the arithmetic section, can store 64 program instructions; its instruction has 32 bits. Each of these instructions is very powerful, as evidenced by the number of bits in the instruction word, so that much can be accomplished in each instruction.

Experience in programming the SPS-81 indicates that our sample problem of Fig. 1 can be partitioned into three overlays: translation filtering with AFC, filtering with envelope detection, and FFT with weighting.

Next the partitioning of the process and the multiple channel capability of the input-output processor must be considered.

- The highest-priority channel can be used to output data to the D/A converter at a clocked rate. The clock rate will be very slow compared to the speed of the processor, and the high-priority channel is used to guarantee a steady output for flicker-free display.
- The next-highest-priority channel can be used to control and move data in and out of the arithmetic section.
- The next-lower-priority channel would contain the post-processing functions.
- The lowest-priority channel would contain data output to the host minicomputer and the executive program.

This prioritized partitioning provides for a natural flow of control from the highest-priority processing channel to the executive in the lowest. When a processing segment is complete on a block of data, the processing of the higher-priority channels stops, causing control to fall through to the next lower priority channel, etc.—finally reverting control back to the executive program. The executive then fetches the next control instruction from computer memory for appropriate action.

The architecture shown in Fig. 2 was chosen to facilitate optimum processing in a parallel pipeline fashion. The control program is resident in the host computer memory where it can be modified by the host minicomputer. Program overlays are stored in bulk memory from which high-speed overlaying of program memory of any internal processor can quickly be accomplished. Processing proceeds under control of the executive program that resides in the SPS-81.

The memory system is also partitioned and distributed to facilitate efficient processing flow. Data is fetched from the dual-port memory for input to the arithmetic section; interim results from the arithmetic section processing are then deposited in a high-speed buffer. Data volume at this point is much reduced, allowing use of the small high-speed memory to hold interim results. The buffer is high speed in that its cycle time is the same as the input-output processor clock.

The post-processing functions are then performed on these interim results. The results may be directly deposited in host memory or in bulk memory for later block transfer to the host minicomputer memory. The display data can be stored in any of the memories for continuous cycled output to the D/A converter.

Microcoding the arithmetic processor is akin to logic design.

Efficient coding of the arithmetic processor requires a somewhat formal programming organization so that the programmer can stay abreast of events at each step of the process. Optimum coding requires maximum use of the arithmetic section at each cycle.The primary difficulty lies in visualization of all the assets and multiplexer switched data paths when attempting to fold in pipelined or parallel processes. The efficient programming and subsequent debugging require careful charting of the processing flow through the arithmetic section.

For this purpose, a charting process has been developed that is akin to logic design. In this technique, the sequential arithmetic section cycles are charted out on a schematic format depicting the arithmetic elements, data paths, and memories. This provides immediate visibility of the state of the arithmetic section at the end of each cycle.

Once the program is mapped, programming requirements for addressing, function selection, scaling, etc., are charted into a table. This table is then analyzed to be sure that arithmetic section waiting time is minimized. The coding plan is juggled to best meet the waiting-time requirement. (At times, this juggling is unsuccessful and it may be necessary to modify the code.)

The input-output processor program is then coded to support the arithmetic-section requirements as coded. Input-output processor constraints may necessitate still another reshuffling of code. The microcoding of programmable processors, therefore, involves logic design with cut-and-fit programming of the various internal processors for efficient throughput. Processing is further enhanced via algorithm tradeoffs which select processing structures that best match the processor.

Speeding up the process

Faster devices are an obvious means of enhancing processing speed; however, the primary challenge is in the selection or design of efficient signal-processing architectures and appropriate programming techniques. The sequential processing and high-level languages found in the general-purpose machine have been replaced with highly parallel structures and machine coding. Although programming these highly parallel processors is more complex, the potential for increased throughput is great. The aim is to provide sufficient switching within the arithmetic hardware to allow optimum programming for a wide variety of signal-processing functions. Both architecture and programming design are tightly coupled with signal-processing techniques and these skills are required for optimum design.

Architecture enhancements: the ultimate goal is to use 100% of the resources 100% of the time.

The most widely used and accepted concept to improve processing speed is a multiple-processor architecture. This concept has been introduced to enhance throughput with a motive for efficient use of the arithmetic unit resources. By providing a separate processor to perform the tasks of input, output, and control, the arithmetic unit can be fully dedicated to arithmetic computation. The approach is to provide an arithmetic processor for computation only and support it with another processor for address computation, data movement, control, and other housekeeping chores.

The memory is in general the slowest device in any signal processor computer structure.

Regardless of the degree of throughput capability achieved with multiple processors and arithmetic unit resources, the cycle times of memories become the limiting factor. Much engineering effort has gone into the design of "smart" memory interfaces and memories to speed computer processing. This type of memory interface is programmed to allow fetching or storing of data arrays at given address increments from a specified starting address, thereby reducing the load on the controlling processor for address computations.

One technique used to overcome the memory speed problem is to distribute the memories (e.g., separating program from the data storage to provide program instruction fetches on a non-interfering basis with retrieving and depositing results in data memories). Distributed data memories and multiple bus structures are also utilized to increase processing speed by minimizing memory wait times. Other techniques applied to reduce memory access time include interleaving memory modules within a single memory on consecutive addresses, and using a small, fast, bipolar memory for scratchpad computation.

Software enhancements: the tradeoffs involve programming techniques as well as the language level employed.

A careful tradeoff must be made between the required performance and computational burden. Both programming and signal-processing ingenuity are essential skills to make this tradeoff. But the potential increase in throughput is high.

The primary effort in software development for computers has been toward higher-level languages. This development proceeds from machine code, to assembly language, to Fortran et. al. to even higher languages, such as those used for structured programming. Each level above machine coding invokes some overhead, and thereby sacrifices processing speed for programming generality. Even assembly code, when it is applied to a particular problem, is not necessarily the most efficient attainable for a particular problem.

The microprogrammable computer breaks this constraint by allowing the programmer to define new computational kernels matched to a particular problem, thus enhancing processing speed by more efficient exploitation of the computer architecture. Microprogramming therefore requires the partitioning of the process to be coded into an efficient set of kernels, followed by microcoding of the kernel.

The coding of programmable signal processors has similar tradeoffs in language level. All of the processor manufacturers provide a basic set of programs (commonly referred to as an array processing library) which can be called at the Fortran level. These libraries include a number of high-level processing functions so that a signal-processing function can be programmed. Use of these libraries, however, involves additional overhead and results in slower overall computational speed.

In general, the integration of the programmable signal processor into a system for real-time radar signal processing will not tolerate this loss in performance caused by extra overhead. It makes no sense to design a processor architecture for optimum efficiency and then throw away much of the performance with setup overhead. To a large extent, overhead will be proportional to processor complexity. Integrating a programmable processor into a real-time signal-processing system, then, imposes a requirement to microcode the application software rather than use the library building blocks.

In summary, speed enhancement via software has three main goals:

1) Selecting algorithms which best fit the architecture of the processor.

2) Partitioning processing functions to minimize overhead.

3) Microcoding the processor to obtain maximum use of the programmable processor's capability.

Conclusions

The programmable signal processor is one of the most important developments in signal-processing applications today. New processors providing greater processing speed and/or flexibility will continue to be developed. The primary effort is in more and more parallelism of one sort or another. Efforts to provide higher-level software will also continue, to ease programming complexity while extracting processing performance. Developers are continually attempting to outreach each other with greater throughput or programming ease, or both. Usually the ease of programming is based on the availability of a library of preprogrammed functions.

Although these libraries have their place, they extract a price in reduced efficiency because of their increased overhead. Each level of parallelism adds, in effect, a level of specialization which makes it much more difficult to develop a higher level language that takes advantage of the efficiencies of the parallel structure.

Application of this type of highly parallel structure to maximize throughput, then, demands that the programming be equally as efficient. The use of microcoding is therefore essential to overcome the inefficiencies of high-level languages. Hence the techniques employed are more akin to logic design. It is clear, then, that the practical implementation of a programmable processor into a system involves not only tradeoffs of system functions, algorithms, and processor structures, but also careful consideration of software design, encompassing the whole range of language levels and associated assemblers and programming aids.

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Comparison of typical programmable processor architectures

The three programmable signal processors discussed here are by no means the only commercially available processors, but were selected because they depict a range of differing architectures and typify the considerations described in this paper.

Some general comparisons

Table I compares the performance that can be achieved on typical signal-processing functions for these processors. Of additional interest, the MAP 300 and AP-120B are floating-point processors whereas the SPS-81 is 16-bit fixed point. Floating point provides greater dynamic range and relieves the programmer of scaling worries.

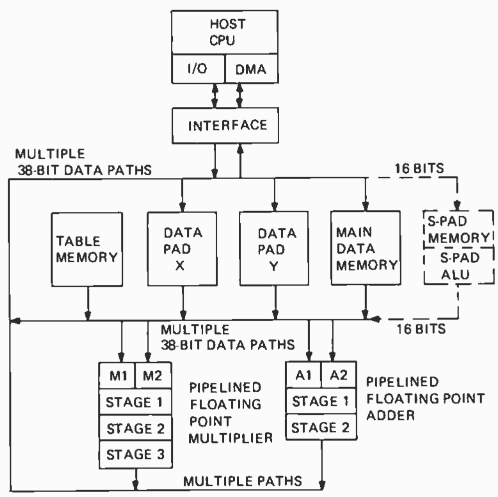
For data I/O the AP-120B and MAP 300 feature independent DMA processors. The DMA processors are set up with a word count, source, and destination address, and increment by either the processor or the host computer. They can then move blocks of data independent (and in the background) of on-going processing.

The SPS-81 has a primary difference in operation in this regard in that all the memories are in effect on the IOP processor bus. There is no need to move blocks of data in and out since it can reach out and fetch data as needed and deposit results in memories or devices requiring them when computed.

Table I
Performance comparison of three commercially available signal processors.

	Processing time, μs/point		
Function	SPS-81	MAP 300	AP-120B
FFT (1024 pt. complex)	3.2	4.5	4.7
Recursive filter (2 pole/2 zero)	0.5	0.85	0.83
Complex mulitply	0.5	0.85	0.67

Array Transform Processor (AP-120B, Floating Point Systems, Inc.). A multiple processor architecture featuring pipeline arithmetic elements, a single interleaved memory, and independent I/O processing.

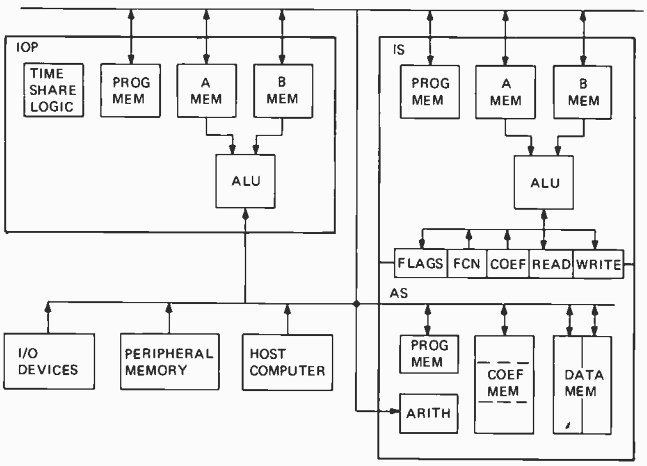


The AP-120B does not function at nearly the multiple-processor level of the other two processors; rather it provides a parallel architecture of varying computational and memory elements controlled from a single program memory. The primary arithmetic elements are a single multiplier and adder which can be pipelined to achieve speed.

Pipelining is a form of parallelism which, in the AP-120B case, is equivalent to three parallel multipliers and two parallel adders. That is, the multiplier of the AP-120B requires three cycles to compute a result; however, additional multiplies can be started before the result is obtained. The AP-120B multiply time is 0.5 μs, but pipelining increases the effective multiply time to 167 ns/computation. The AP-120B adder is also 2:1 pipelined, with a single multiply taking 333 ns and a pipeline rate of 167 ns/computation.

The architectural simplicity of the AP-120B arithmetic unit is deceptive in terms of programming difficulties. To obtain processing efficiency, the programmer must constantly visualize the time phasing of data in and out of memory and arithmetic elements. Also, the multiple processors of the AP-120B are not totally independent, since they operate from a single program memory.

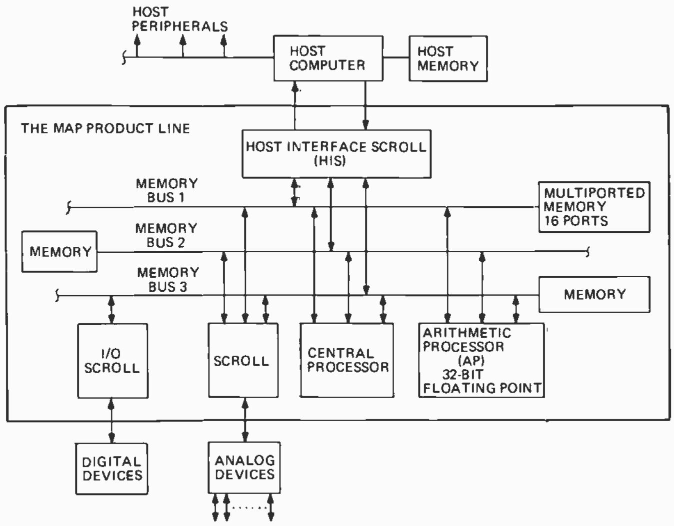
Programmable Digital Signal Processor (SPS-81, SPS, Inc.). This processor architecture features a highly parallel, number-crunching arithmetic processor (IS and AS), supported by a fast microcomputer-like I/O processor.



The three processors of the SPS-81 have independent program memories and they operate independently. The machine is synchronous in that the clocks for each processor are derived from a common source. The cycle time of the input-output processor and index section is 167 ns. The SPS-81 can do a full complex multiply (four real multiplies plus two adds) and two full complex adds (four real adds) in 0.5 μs. A hardware multiply in the input-output processor can also speed processing when use of the complex arithmetic processor is inappropriate.

In addition to being one of three processors, the SPS-81 input-output processor is itself a four-channel processor, thereby further extending processor parallelism. A memory register file, program counters, and control are replicated four times. Operation of the four channels is on a time-share basis. If a channel is waiting for a memory cycle to complete, the next-lower-priority channel can perform a computation in the arithmetic logic unit, service a device, or fetch data from an alternate memory.

Macro Arithmetic Processor (MAP-300, CSPI, Inc.). A multiple processor with a multiple-bus, multiple-memory architecture and separate, independently programmable I/O processors.



The MAP is also a federation of independently programmed parallel processors. The MAP is unusual in that is is a totally asynchronous processor. Operations are not clocked as in other processors; rather operations flow from one to the next as needed data or operands become available. Processing proceeds at device speed, theoretically obtaining maximum computational speed available from given devices. The MAP-300 performs two multiplies in 0.42 μs plus two adds in 0.21 μs (i.e., one in each arithmetic element), for an effective rate of 0.21 μs and 0.105 μs respectively.

The two arithmetic processors proceed similarly. As operands become available in the arithmetic-element input registers, computations proceed. If compuation results are required as inputs to the next computation, the next operation proceeds as soon as the previous result ripples into the operand register. Synchronism between processors is achieved on a programmed basis with flags and status bits.

Digital computer simulation of radar systems

J. Liston | G.M. Sparks

Simulation is a necessity for radar systems as complex as AEGIS. Without it, problems and optimizing would appear too late in the design process.

This paper provides an overview of the kinds of simulation models, together with their application to radar systems design and analysis. The simulations discussed in this paper are broadly categorized as real-time and non-real-time simulations. A real-time simulation includes real-time cycling constraints associated with operation in a realistic scenario. An example is a real-time operational simulation, which facilitates the routine evaluation and parameter "trimming" of an illustrative aircraft vectoring system without the necessity for flight support aircraft. A non-real-time simulation, on the other hand, is not constrained by the real computation time; however, such a simulation is a powerful tool for designing and evaluating algorithms and functional interrelationships in a complex radar-centered system.

Within each of the foregoing categories, the elements of the system to be simulated are categorized as discrete or analog processes. Discrete processes are usually described by difference equations and can be directly programmed on a digital computer. These processes, such as those employed by digital signal processors, are usually simulated on a general-purpose digital computer by simply using the Fortran (or other high-level language) equivalent of the specific algorithm associated with the process in question. Analog processes are usually described by differential equations, so to program these equations it is necessary to convert them to a set of difference equations. The initial form of the process may be a set of differential equations or a transfer function, $G(s)$, which represents a set of differential equations. The approach to converting the analog process to a discrete process may be to solve the set of differential equations and to sample the solution at discrete intervals or to use transforms such as the bilinear transformation to develop the difference equations directly from the Laplace-transform transfer function, $G(s)$. Recursive algorithms can be used for either approach.

Discrete and analog process simulations can be realistically integrated to represent the operation of a complex radar system or perhaps certain critical elements of the system. This paper describes how the effects of noise, thresholds, nonlinearities, system errors, quantization, and various aspects of the system environment (propagation, multipath, etc.) are introduced and how each affects the overall system. It also gives specific examples on the simulation effort that RCA Missile and Surface Radar has used in the design and evaluation a number of radar systems.

Simulation approaches

Most processes encountered in the study and analysis of radar systems can be classified as either analog or discrete. Analog processes have a continuous time response to a given excitation function and, as such, are best described in terms of differential equations or Laplace transforms expressed as functions of the complex frequency variable; i.e., $G(s)$. Discrete processes, on the other hand, have process variables defined only at a particular set of time values, implying that the independent variable (time) is quantized. Such processes are typically described in terms of difference equations which can be directly programmed for solution on a digital computer.

One way of simulating analog processes on a digital computer is by solving the defining differential equation directly.

For some analog processes described by a set of N simultaneous linear constant-coefficient differential equations with M time-varying inputs, it is more efficient to solve the equations and store the results as an $N \times N$ and an $N \times M$ matrix in a data file, rather than use substitution techniques such as the bilinear transform. This data file is then available to the appropriate simulation program and can be executed by simple multiplications and additions at the system data rate. Substitution methods or numerical-integration techniques sometimes require integration time intervals much smaller than the computer system update time interval.

To illustrate this approach consider the scalar differential equation:

$$\dot{X}(t) = AX(t) + B\mu(t) \tag{1}$$

The solution to this equation is:

$$X(t) = e^{A(t-t_k)}X(t_k) + \int_{t_k}^{t} e^{A(t-\sigma)}\, B\mu(\sigma)d\sigma \tag{2}$$

where $X(t_k)$ is the initial condition and $\mu(t)$ is a time-varying input.

This is the solution to an analog process. For a discrete process, the equivalent solution is

$$X[(k+1)T] = e^{AT}X(kT) + [e^{AT}-1](B/A)\ \mu(kT) \tag{3}$$

This equation then solves for a sequence $X(kT)$ for $k = 1, 2,\ldots$ using an input sequence $\mu(kT)$ for $k = 1, 2,\ldots$. This solution can be used in a feedback system where $\mu\ (kT)$ is a function of previous values of X.

Eq. 3 is the solution to a single differential equation with one input. Consider now N differential equations with M inputs. The solution to these equations can be written in matrix form similar to Eq. 3.

The resulting matrix equation is written in the following general form:

$$X[k+1)T] = \alpha X(kT) \pm \beta\mu(kT) \tag{4}$$

where α and β are respectively $N \times N$ and $N \times M$ constant matrices.

The key to this solution is to determine the matrix $\underline{e}^{\underline{AT}}$ in order to arrive at $\underline{\alpha}$ and $\underline{\beta}$. The matrix $\underline{e}^{\underline{AT}}$ is computed by calculating the eigenvalues and eigenvectors of $\underline{A}$ and performing the appropriate transformations. This was a very convenient method, since the time-shared computer system available at RCA MSR had library routines which calculated eigenvalues, eigenvectors, and matrix inversions. A separate program used these library routines to calculate and store $\underline{\alpha}$ and $\underline{\beta}$ so that they were then available in a data file for use by a simulation program.

In substitution methods, the differential equation or its Laplace transform is represented as a discrete process that closely approximates the time response of the analog process.

Fryer and Schultz[1] describe various methods of simulating system transfer functions on a digital computer. These methods yield solutions that are expressed in terms of a recursive or difference-equation form, through the substitution $s = (2/T)(1-\Delta)/(1+\Delta)$ when T = time interval between data points and Δ = delay operator e^{-sT}.

$$G(s) \rightarrow G[f(\Delta)] = \frac{a_0 + a_1\Delta + a_2\Delta^2 + \ldots + a_m\Delta^m}{1 + b_1\Delta + b_2\Delta^2 + \ldots + b_m\Delta^m} \qquad (7)$$

The corresponding difference equation or recursion formula is written by inspection as

$$\begin{aligned} y_n = a_0x_n + a_1x_{n-1} + \ldots + a_mx_{n-m} \\ -b_1y_{n-1} - b_2y_{n-2} - \ldots - b_my_{n-m} \end{aligned} \qquad (8)$$

which can immediately be programmed on a digital computer. Fig. 1 gives a flowchart for such a program. Table I is a short table of bilinear transforms which give the values of the coefficients (a's and b's) in terms of the parameters of the transfer function $G(s)$ and time interval T. We note that the bilinear transform can be cascaded; that is, if $G(s)$ can be factored into the form

$$G(s) = G_1(s)G_2(s)$$

$G_1(s)$ and $G_2(s)$ can be programmed into two independent blocks of code and the output of the $G_1(s)$ simulation used to provide the input to the $G_2(s)$ simulation. The resulting output of the $G_2(s)$ block, under this condition, will simulate the output of $G(s)$.

The difference equation that is the result of the bilinear transform process is easily programmed; however, evaluating the constants a_0, a_1 ..., b_1, b_2 ... can involve a considerable amount of tedious algebraic manipulation, particularly in the case of high-order polynomials in s. However, this algebraic manipulation can be carried out using a digital computer, thus relieving the user of the burdensome algebraic manipulation and reducing the possibility of introducing errors in the process. The method assumes that the function $G(s)$ to be simulated is of the form of the ratio of two polynomials in s.

Table I

Bilinear transforms (or Tustin transforms) convert Laplace transforms into discrete difference equations that are easily programmed on a digital computer.

Network	$G(s)$	y_n
Integrator	$1/s$	$(T/2)(x_n - x_{n-1}) - y_{n-1}$
Lag network	$1/[(s/b) + 1]$	$[Tb/(2+Tb)]\,x_n + [Tb/(2+Tb)]\,x_{n-1} + [(2-Tb)/(2+Tb)]\,y_{n-1}$
Lead-lag network	$[(s/a) + 1]/[(s/b) + 1]$	$[b(2+Ta)]/[a(2+Tb)]\,x_n + [b(Ta-2)]/[a(Tb-2)]\,x_{n-1} + [(2-Tb)/(2+Tb)]\,y_{n-1}$

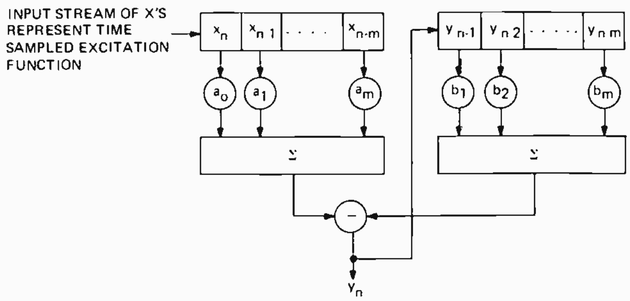


Fig. 1

Flowchart for program solving the difference equations of the type given in Table I.

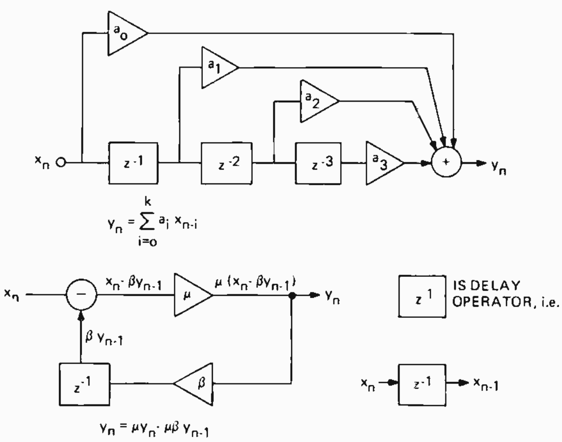


Fig. 2

Simulated digital filter is a result of using difference equations derived from knowledge of transfer functions or by tracing the signal flow.

Simulation of discrete processes, such as digital filters, on a general-purpose digital computer is a straightforward procedure.

Fig. 2 shows illustrative digital filters and the corresponding difference equation that provides a discrete time series of output values, y_n, given a time series of input values, x_n. Such difference equations can be directly programmed on a general-purpose computer to exactly represent the discrete process of interest. The difference equations are derived from knowledge of the transfer functions appropriate to certain classes of digital filters[5]; e.g., direct form 1, direct form 2, parallel form, or in certain simple cases, by tracing the signal flow as implied by the examples in Fig. 2. Noise, signal-amplitude quantization effects, and logical operations can also be readily accommodated within the framework of a suitable high-level computer language such as Fortran.

In certain cases, the discrete process is defined in terms of an algorithm, which can be directly transcribed into simulation code. For example, a specific fast-fourier-transform algorithm used in a radar digital signal processor can be directly coded into a Fortran simulation of the processor.

Examples of small-scale analysis by simulation

Simulation can help analyze the central issue in many radar signal-processing systems—detection performance.

In order to illustrate a general methodology for such cases, let us use digital or Monte Carlo simulation to determine the target detection probability, given a specific signal-to-noise ratio and false alarm probability. The theoretical solution to this problem is well known,[6] thus we can compare simulation-derived and theoretical results to gain a feeling for what can be achieved in terms of accuracy.

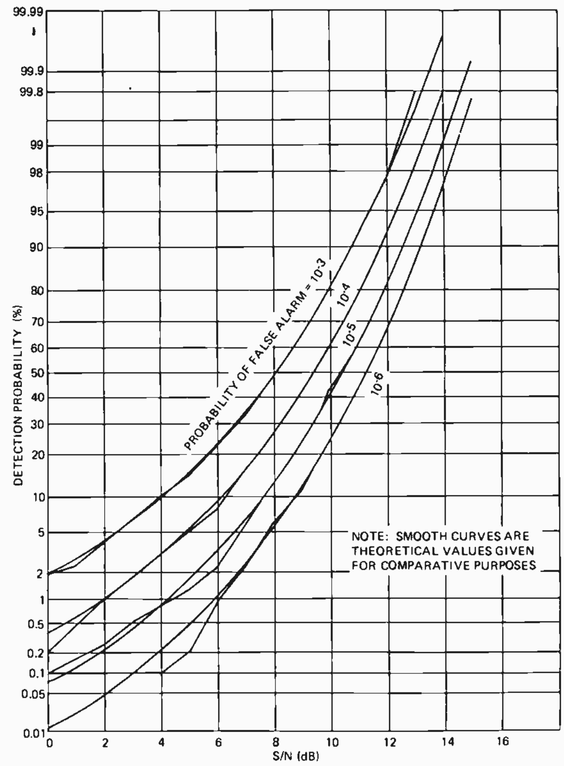


Fig. 3
Good comparison exists between theoretical (smooth curves) and simulated probability of detection.

Consider that the output from a linear detector, which provides the envelope of steady sinusoidal signal plus noise, is statistically governed by the modified Rayleigh distribution. This process is simulated by forming the vector sum of a steady signal and independent in-phase and quadrature-phase noise samples from a Gaussian distribution of zero mean and unity variance. A simple threshold detector can then be simulated by generating voltage samples in accordance with the above procedure and comparing the resulting amplitudes with a threshold given by

$$T = (-2 \log_e P_{fa})^{1/2} \qquad (9)$$

where P_{fa} is the false-alarm probability.

Some insight as to the accuracy of our signal-plus-noise simulation can be obtained by calculating detection probability versus signal-to-noise ratio (S/N) for various values of false-alarm probability and comparing the results with theoretical values computed with a highly accurate algorithm.[7] This has been done in Fig. 3 for 2000 Monte Carlo trials; correspondence with theoretical values is excellent.

Simulation is not limited to cases in which the radar signal is steady.

It is possible to simulate amplitude samples of the envelope of signal plus noise where the signal components are fluctuating. Such fluctuations arise due to changes in the relative phase relationships* among the various scattering centers which comprise the target. The fluctuations can be classified as either independent from sample to sample (rapidly fluctuating) or totally correlated within a given stream of samples (slowly fluctuating). Here, the stream of samples might simulate the sequence of target returns which occur as the radar beam scans past a target during a single rotation (or scan) of the antenna.

Additional effects which influence the amplitude of the signal returns include the antenna pattern shape and reflections from the surface or other large objects in the vicinity of the radar. These are accounted for in many simulation analyses, but will not be discussed in detail here.

Radar system simuation is often called upon to provide a model of the dynamic effects of a moving target of interest.

The simulation generates a realistic time sequence of radar measurements (observables) in terms of range, azimuth, and elevation. These values are modeled to represent the "true" position of the target. The resulting time sequence of observables are then perturbed within the simulation to represent the effect of radar-induced "noise" on the process under analysis.

Simulation showed how adding a sidelobe blanker affected system performance.

A sidelobe blanker inhibits receiver response to signals which enter the radar via the antenna sidelobes. The gate into which the reference and blanker channels respectively feed passes the reference-channel signal-plus-noise only if the envelope of the signal-plus-noise of the reference channel exceeds that of the blanker channel by a specified blanker threshold, expressed in dB. If blanker threshold is exceeded, a single pulse "detection" or "hit" is declared if the envelope of signal-plus-noise exceeds the threshold established in a second gate. For linear envelope detection, this threshold value is given in accordance with Eq. 9.

N successive beacon response samples, characterized by a given reference-channel signal-to-noise ratio, are considered in the simulation. The detection probability is

*Due to changes in signal frequency (frequency diversity) or target rotation relative to the radar line of sight.

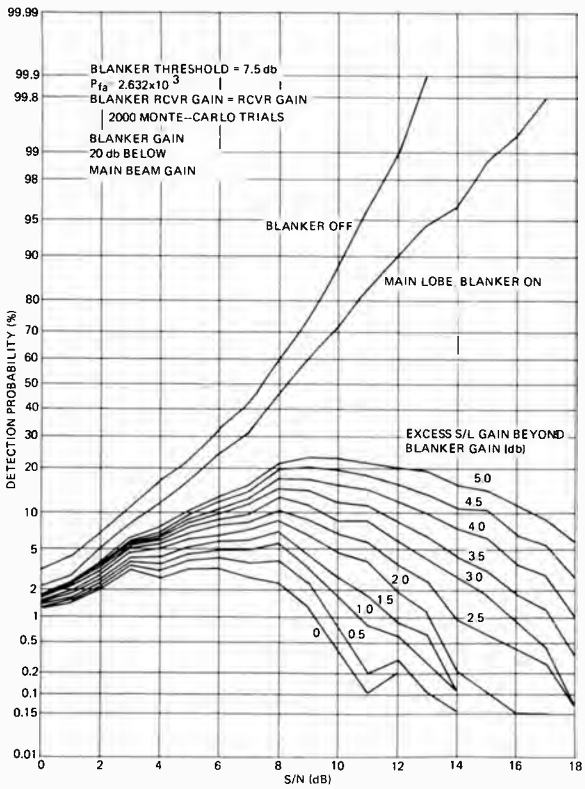


Fig. 4
Sidelobe-blanker simulation showed the loss in detection (two curves) performance that occurs when sidelobes are blanked out as an electronic counter-countermeasure. Set of 11 curves shows probability that sidelobe (S/L) signals will be falsely accepted as a mainlobe signal.

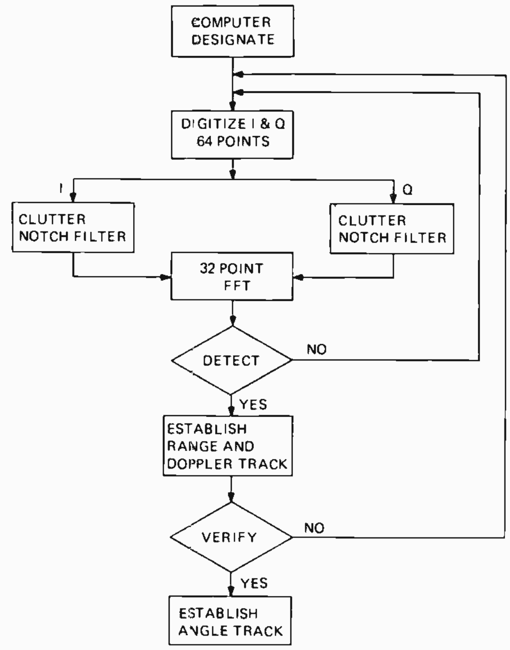


Fig. 5
Simulation of artillery-shell detection was useful in quantizing and scaling system during development, then debugging in field. I and Q are in-phase and quadrature signals.

then computed as ratio of the accumulated number of "hits" to the number of trials, N. For each trial, independent samples of in-phase and quadrature-phase Gaussian noise perturb the signal levels in the respective reference and blanker receiver channels. The effect of the reference-pattern beam shape loss or sidelobe attenuation on the reference-channel signal levels is accounted for in establishing respective signal-to-noise ratios in the reference and blanker receiver channels. Typical results obtained with such a simulation are shown in Fig. 4. These results show the loss in detection performance which is introduced by the blanker circuit; they also indicate the probability that a sidelobe signal will be falsely accepted as a mainlobe signal for various values of sidelobe gain greater than the blanker antenna gain.

Another program simulated a clutter filter and Fast Fourier Transform on an AN/MPS-36 radar modification.

This system problem was one of automatically detecting, acquiring, and tracking a high-speed artillery projectile with a pulse doppler radar in the presence of ground clutter. The goal was to complete the detection and acquisition process in less than one second.

The signal-to-clutter ratio (S/C) when attempting to acquire the target was approximately -30 dB. To acquire the target it was necessary, via signal processing, to improve this by 43 dB to an S/C of 13 dB.

The signal processor had available in-phase (I) and quadrature (Q) signals. Each of these signals was processed through a three-pole Cauer notch filter which gave a stop-band rejection of 51 dB. The I and Q were then processed with a 32-point Fast Fourier Transform (FFT). The output of the FFT was 32 signals equally distributed over a radar pulse repetition interval (PRI). The target doppler frequency and amplitude was determined by examining these 32 signals and performing a $\sin x/x$ interpolation between the largest returns. A threshold was then examined and, if it was exceeded, a target detection was declared. A three-pole bandpass filter then verified if this was indeed a target.

The entire detection process, shown in Fig. 5, with a clutter signal, target signal, and receive noise, was simulated on a digital computer. The program was set up to randomly select both a PRF and a doppler frequency within the middle 50% of the PRI. Using an $S/C=-30$ dB, 80 detections were made. The calculated doppler for each detection was within $\pm$ 10 Hz of the true doppler. This simulation program was also very useful in investigating such things as the effect of quantizing and scaling. It proved extremely useful in debugging operations in the field.

Examples of large-scale system simulations (non-real time)

The AN/MPS-36 instrumentation tracking radar was the subject of a detailed computer simulation.

A data rate approximately equal to the pulse repetition frequency was used and all radar functions, modes, and conditions were included. The basic modules of the program are:

Trajectory generator—target trajectory

Target effects—signal return from target

Power program and transmitter

Atmospheric effects—clutter and multipath

Automatic gain control

Track servos—azimuth, elevation, range and doppler (range rate)

Systematic errors

Random errors

Executive control—controls system by making *a priori* and real-time decisions

In simulating missile targets, the launch point, impact point, and trajectory can be programmed and either a passive echo target or a beacon-transponder target can be selected. The passive target consists of a cone-cylinder missile configuration with user-selected dimensions and a resulting radar cross section varying realistically with viewing aspects. For the beacon target an *N*-antenna-port system equally spaced about the missile, including resulting polarization and interferometer effects, is simulated. The simulation also includes range delay and doppler shift for echo or coherent-beacon targets.

The simulated electromagnetic environment includes error contributions caused by atmospheric refraction, ground clutter, and multipath. The multipath effects consider the diffraction, intermediate, and interference regions. The radar model includes the effects of the radar data processor so that the output data obtained from either the real radar or the simulated radar will have been identically processed.

All four of the radar tracking channels (azimuth, elevation, range, and range rate) were simulated using the same approach. First, detailed mathematical representations of the track circuitry were developed in the frequency domain. These expressions were then transformed into difference equations for digital simulation.

TPQSYM simulates the operation of the AN/TPQ-27 precision tracking radar, tracking filters, and all the guidance algorithms necessary to guide a "simulated" aircraft model on a radar-directed bombing-mission flight path.

Ballistic drag tables are stored within the program for a variety of bomb types along with a fourth-order Runge-Kutta integration routine to solve the ballistic equations of motion for the falling bomb. Major features of TPQSYM are as follows:

All four TPQ-27 guidance modes are incorporated;

F4 aircraft flight dynamics is based on high-degree polynomial representation of aircraft using manufacturer's data;

lateral and pitch control of aircraft is provided;

wind effect on the aircraft and bomb trajectory is accounted for;

earth's curvature between radar site and target is accounted for through a rotation matrix;

radar noise and bias effects can be specified;

input data (R, A, E) can be obatined from a recording of field-derived data (actual) or simulated on the basis of interval noise generators;

a wide variety of plots can be specified and made by the user; and

TPQSYM currently runs on MSR time-shared system in Fortran.

Fig. 6 shows a typical plot obtained from TPQSYM. This plot represents the altitude-control-channel response to an initial altitude error of 200 ft, given an F4B aircraft at a nominal 2000-ft. altitude and 500-knot airspeed.

A dynamic, single-target, weapon-system simulation measures AEGIS performance against contemporary threats in hostile, uncooperative environments.

This simulation, known as *S*ystem *P*erformance *E*valuator *C*omprising *T*arget, *R*adar, *M*issile (SPECTRM) models a target generator, the AN/SPY-1 phased-array radar, Mk91 slaved illuminator, SM-2 missile, and ship's motion along with the Mk19 gyro. Developed over the past seven years, SPECTRM is still undergoing changes which reflect field alterations, and additions which are included as new operating modes become viable.

To date, SPECTRM has had a variety of uses, including:

initial verification that slaving an illuminator to SPY-1 outputs was feasible against a wide spectrum of targets;

error budget analysis (error sensitivity and allocation); design and verification of a universal range-adaptive α, β-filter for weapons-system users;

measuring AEGIS performance against specification targets; developing 'special case' system logic, such as low-E-mode logic and coast-mode logic;

determining system performance against special threats;

assessing effect of face-to-face (array-to-array) handover errors on missile/target track, verifying that single-face testing was adequate;

assessing efficiency of various midcourse guidance laws for missile flight control;

comparing capabilities of several proposed rocket motors;

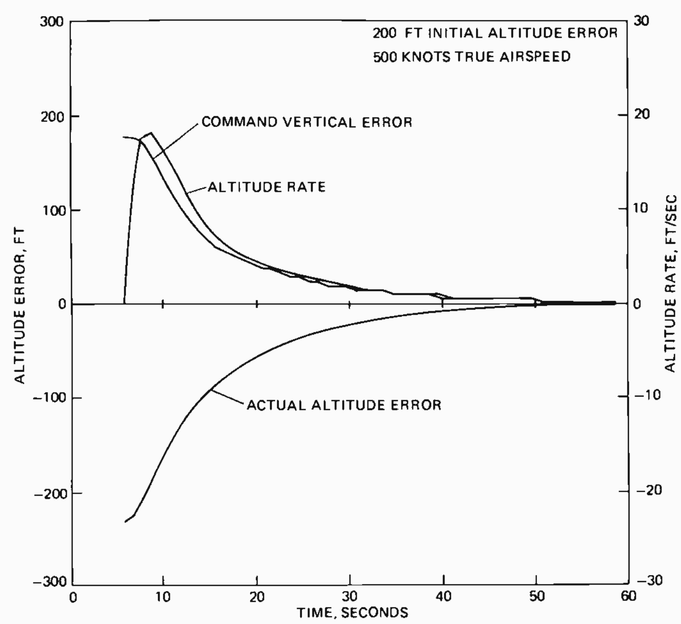


Fig. 6
Tracking-radar simulation is possible with TPQSYM program. Plot represents the radar's altitude-control response to an initial altitude error of 200 ft.

developing missile 'fly-out' curves; and

determining AEGIS performance in an ECM environment.

SPECTRM contains about 5000 Fortran statements, and requires approximately 300,000 bytes of memory. The program is extensively modularized and, through the use of control cards, only those equipments essential to the particular analysis need be exercised. In addition, the many system noise sources can be individually selected—or omitted entirely if a 'reference run' is desired. When the entire weapons system is under analysis, program running time is approximately three times faster than real time.

The MEDUSA simulation evaluates the performance of the AEGIS system against multi-target attacks.

MEDUSA (*M*ulti-target *E*ffectiveness *D*etermined *U*nder *S*imulation for *A*EGIS) is written in Fortran and currently requires approximately 160k words of DEC20 storage. It includes models of the SPY-1 radar, Mk 26 launcher, Mk 91 illuminator, SM-2 missile Combat Air Patrol (CAP) and software logic to control these equipments. Models to describe enemy scenarios are also provided.

The specific uses for MEDUSA are to provide:

a test bed to aid the design and evaluation of AEGIS tactical algorithms

an operation analysis tool to assess the tactical performance of AEGIS

assistance for AEGIS test analysis

MEDUSA has been successfully used as a test bed to evaluate candidate SM-2 scheduling algorithms and Threat Evaluation Weapon Selection (TEWS) algorithms. The modular structure of MEDUSA allows the simulation of an unlimited number of candidates for each AEGIS algorithm being evaluated. The algorithms for a particular run are specified by input parameters. MEDUSA is also capable of acting as a test bed to aid the design and evaluation of other Weapon Control System (WCS) and Command and Decision (C&D) algorithms. MEDUSA is not intended to be used to design AEGIS equipment. Models of the SPY-1 radar, Mk26 launcher, Mk91 illuminator, and the SM-2 missile are part of the MEDUSA test bed.

Trajectory-generator subprograms to model threat targets are also included in the test bed, as are default models for the algorithms being evaluated. The test-bed models are intended to have sufficient fidelity to provide valid results in the evaluation of tactical algorithms or system tactical performance. In general, this does not require that the models mimic in detail the equipment or phenomena they represent. Greatly simplified models are used wherever possible in the interest of simulation computer program development and running time costs.

As system design continues, more specific requirements for MEDUSA runs develop and with them come concomitant requirements for additional sophistication in some of the models. The modular structure of MEDUSA permits ready modification or replacement of the models (either those representing algorithms under test, or those making up the test bed) as the need arises. In the meantime, evaluations requiring only simple models are not delayed pending availability of the "ultimate" MEDUSA.

MEDUSA is now available for both pre-test and post-test analysis for actual AEGIS tests at the Combat Systems Engineering Development site. Currently MEDUSA is being used to design scenarios before they are run on the AEGIS Interface System Simulator. This is an inexpensive way to uncover anomalies in the scenarios.

Real-time simulation of large systems

The develoment of radar command and control computer programs frequently occurs parallel with hardware development. The computer systems now contain functions which in the past were hardwired. Many of these functions, such as closure of angle servo loops, closure of range loops, target acquisition, target detection, and waveform selection, are implemented in computer programs, making the computer system an integral part of the radar system design.

To test the system, therefore, it is necessary to integrate the hardware and software. As the complexity of computer programs increases, a means of verifying the performance of the computer programs prior to hardware integration is needed to assure that schedule and cost objectives can be obtained.

Real-time simulation, therefore, has an important role to provide a real-time interface which can be used as a certification and maintenance tool to:

reduce costs over the total program, as the simulator

—does not require the use of a live hardware environment for operational computer program testing

—allows for parallel testing of hardware and computer program prior to and after integration.

minimize risk in development by

—providing a means for early detection of problems

—providing management with visibility of the program-development cycle and allow for action to be taken in problem areas

—assuring that problems in the computer programs and/or hardware do not paralyze independent testing of both

provide a means of verifying computer programs during acceptance testing and after implementation of approved computer program change requests.

TPQSIM verifies the AN/TPQ-27 operational program and conducts software acceptance tests in a controlled environment; i.e., without the need for physical radars and aircraft.

TPQSIM operates on the PDP-11/70 computer. It simulates, in real time, an IFF (identify friend or foe) radar, a precision tracking radar (PTR), a Tadil-C data link, and several aircraft. TPQSIM communicates with a program running on an AN/UYK-7 computer across a special-purpose hardware interface. The heading and attitude of each of the aircraft can be modified by Tadil-C messages. Messages concerning IFF and PTR detections, beam-steering commands, weapon-release signals, etc., are sent between the two computers in formats and rates identical to those used in the AN/TPQ-27 operational program.

TPQSIM is valuable because it:

exercises computer programs in real time without requiring live aircraft;

provides simulated I/O channel interface data for IFF, PTR, and communications functions,

generates dynamic aircraft positional data on line;

includes functional tracking radar hardware simulation for angle-error and range estimation;

includes functional IFF radar hardware simulation for antenna motion, azimuth estimation, and range estimation;

does not interfere with basic operational program timing;

does not require modification of basic operational computer programs;

synchronizes I/O using a real-time clock; and

allows for test operator control.

The AEGIS Interface Simulation System computer programs test the AEGIS tactical computer programs.

The interface simulators consist of an integrated, modular set of computer programs that can be tailored to simulate unavailable interfaces; e.g., comptuer programs and/or equipment and external stimuli; e.g., targets to the tactical computer programs. The interface simulators provide a test bed to support the verification, integration, test, and acceptance of the tactical computer programs during the various stages of their development. The interface simulators are used to support:

the tactical computer program system element builds and Phase II tests at the Computer Program Test Site (CPTS);

multi-element computer-program integration and test at the CPTS; and

Combat System integration and test at the Combat Systems Engineering Development Center (CSED).

The ISS computer programs operate in sets of two-bay and three-bay AN/UYK-7 computers and use a common user language (SCRIPT) and a common control system.

The ISS computer programs include several on-line programs which provide input to exercise the following segments of the AEGIS combat sysem:

AN/SPY-1A phased-aray radar—the basic AEGIS sensor;

C&D (Command and Decision), which drives displays and reacts to operator command;

ORTS (Operation Readiness Test System), which provides on-line monitoring;

GDC (Gyro Data Converter), which simulates ship's motion;

WCS/FCS (Weapons Control System/Fire Control System), which computes launch parameters and aiming angles for the missile launcher; and

SYSTEM, which exercises all system components as a complete system.

Concluding remarks

We have presented a summary of the kinds of digital simulations which have been used at MSR during the past few years to design, troubleshoot, and validate a variety of radar systems. Specific examples have been drawn from the AN/MPS-36, AN/TPQ-27, and AEGIS programs. Such simulations have made a vital contribution towards the development of these systems.

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Jack Liston has held major systems responsibility for concept design, performance analysis, and design optimization on advanced phased-array radar system developments. Some of the areas of his principal contributions include system computer modeling for cost optimization and performance tradeoffs, advanced self-duplexing receiver concepts, and system performance verification through simulation. He is now systems engineer on the AN/TPQ-27 radar.

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Enhancing antenna performance through multimode feeds and distribution networks

C.E. Profera

Parabolic antennas have high efficiency and gain when they are fed by electromagnetic energy that is radiating in more than one waveguide mode.

Probably the most widely used microwave antenna is the paraboloid reflector, illuminated by a source of electromagnetic energy called the feed, which is placed at the focal point of the reflector. The feed directs energy toward, and receives energy from, the reflector surface. The paraboloid reflector antenna radiates (or receives) energy in a prescribed pattern characterized by a single dominant narrow main beam or lobe and a plurality of lower-level minor lobes or sidelobes.

Reflector antennas that are required to exhibit optimum performance (generally implying maximum efficiency of antenna illumination by the feed and minimum sensitivity to external noise) are often illuminated by a Cassegrain[1] feed system as shown in Fig. 1. Such a feed system consists of a secondary hyperboloid subreflector and feed. In this configuration the feed directs and receives energy to and from the subreflector surface. The subreflector, in turn, directs and receives energy to and from the main paraboloid reflector surface.

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The feed, for either the conventional paraboloid reflector antenna or the Cassegrain antenna, is generally an electromagnetic waveguide horn connected to the associated system transmit/receive network by waveguide transmission line. The simplest horn feed that may be used is one which propagates and radiates the electromagnetic field characterizing the fundamental or dominant waveguide mode, denoted TE_{10} mode for general rectangular waveguide structures. Feeds of this type are always designed so that the only electromagnetic wave propagated and radiated characterizes the fundamental mode.

Horn antenna technology advancements in the 1960s included the discovery of a higher-order waveguide mode radiation property. When combined with fundamental mode radiation, this property produces feed radiation characterisitics leading to subsequent antenna performance enhancements.[2] The most notable improvements obtained relate to antenna efficiency. The primary advantages of this dual-mode radiation principle are reduced feed-pattern sidelobe levels and improved feed-pattern main-beam symmetry. These feed radiation properties produce lower spillover loss (i.e., feed radiation outside the boundaries of the collimating reflector system) and a symmetric reflector illumination characteristic, both of which increase antenna gain.

Additional specific higher-order waveguide modes produce the radiation-pattern characteristics necessary to perform monopulse radar tracking.[3,4] The ability to independently generate and control the multiple modes required for improved performance and monopulse tracking, within a single waveguide horn feed, has led to the development of the multimode monopulse feed. This feed configuration is the high-performance standard for tracking radar applications employing Cassegrain reflector antennas.

The low-sidelobe illumination properties provided by the multimode feeding technique are also applicable to antenna configurations employing horn feeds for phased-array antennas.[5] Multiple-mode, low-sidelobe distribution networks for both planar[6] and circular-array[7] antennas have been developed using this technique.

This paper presents the fundamentals of multimode feed techniques and describes both the reflector-antenna and phased-array applications where these techniques have been employed.

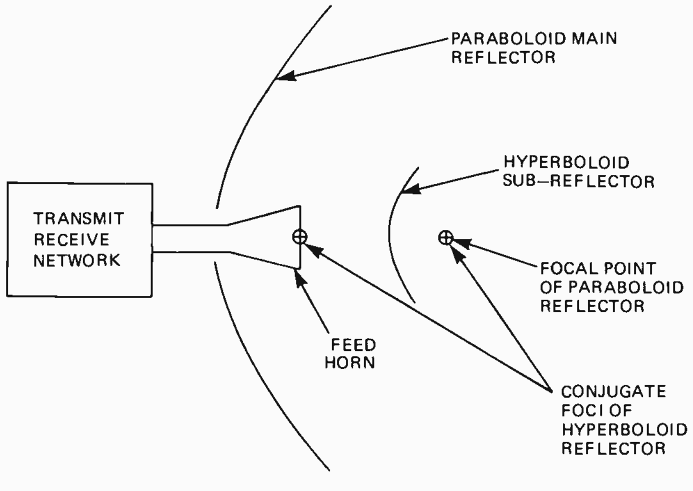


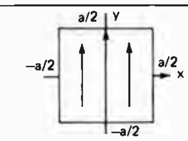
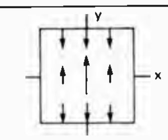
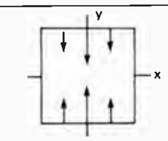
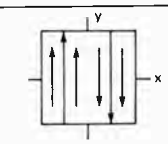
Fig. 1
Cassegrain reflector antenna system cross section illustrates the relationships among the feed horn, the confocal hyperboloid subreflector, and the paraboloid main reflector.

Multimode fundamentals

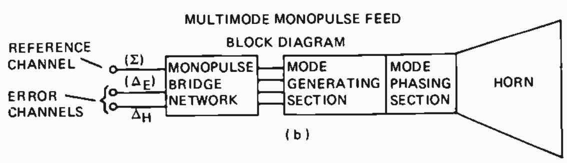
Monopulse tracking radar system requirements for reflector antennas with optimum high-gain and low-noise properties are most readily satisfied by the dual-reflector Cassegrain antenna with a multimode, monopulse feed.

This application of multimode technology is the one of most general interest at RCA MSR. Multimode fundamentals are

(y– POLARIZED FIELDS)

MODE TYPE	E (x,y) (y– POLARIZED FIELD)	TRANSVERSE FIELD ILLUSTRATION (y– POLARIZED FIELD)
TE_{10} (Σ)	$\cos \frac{\pi x}{a}$	
LSE_{12} ($TE_{12}+TM_{12}$) (Σ)	$\cos \frac{\pi x}{a} \quad \cos \frac{2\pi y}{a}$	
LSE_{11} ($TE_{11}+TM_{11}$) (Δ_E)	$\sin \frac{\pi y}{a}$	
TE_{20} (Δ_H)	$\sin \frac{2\pi x}{a}$	

(a)



(b)

Fig. 2
Trigonometric functions and transverse electric fields are illustrated (a) to describe the feed aperture distributions produced by each of the modes of a high-performance multimode monopulse feed. The block diagram (b) shows the major functional sections of a typical multimode monopulse feed.

described here in terms of the monopulse application, but the techniques used are applicable, in a non-monopulse sense, to high-performance reflector antennas in other radar and non-radar applications.

The single-polarization waveguide mode set employed in a high-performance monopulse feed application contains the fundamental TE_{10}, and higher order TE_{12} + TM_{12} (called LSE_{12}), TE_{11} + TM_{11} (called LSE_{11}) and TE_{20} rectangular waveguide modes. The mathematical functions describing the transverse electric fields of these modes (in square waveguide) are tabulated in Fig. 2, along with their field configurations and a block diagram of a typical feed system that produces them.

The electric field composed of a sum of waveguide modes is "tapered" to control the beamwidth and sidelobe patterns of the feed.

The reference or sum channel of a conventional four-element monopulse comparator network connected to a multimode feed produces, at the feed aperture, an electric-field distribution composed of the sum of TE_{10} and LSE_{12} waveguide modes. Combining these modes produces a resultant electric-field distribution whose transverse amplitude (x-y plane), in a square feed aperture, is represented

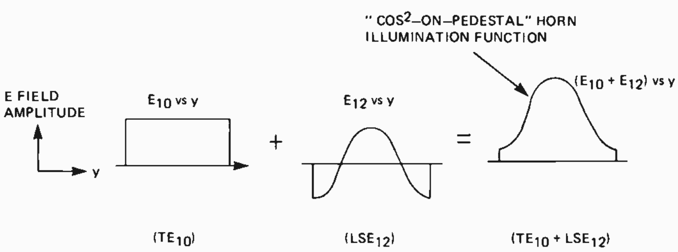


Fig. 3
E-plane feed aperture "tapering" shown here results when the TE_{10} and LSE_{12} modes are summed in a co-phased sense. The resulting "$\cos^2$-on-pedestal" distribution is produced by summing the uniform TE_{10} mode and cosine-tapered LSE_{12} mode E-plane distribution.

Fig. 4
E- and H-plane sum and difference pattern functions of a well-designed multimode feed.

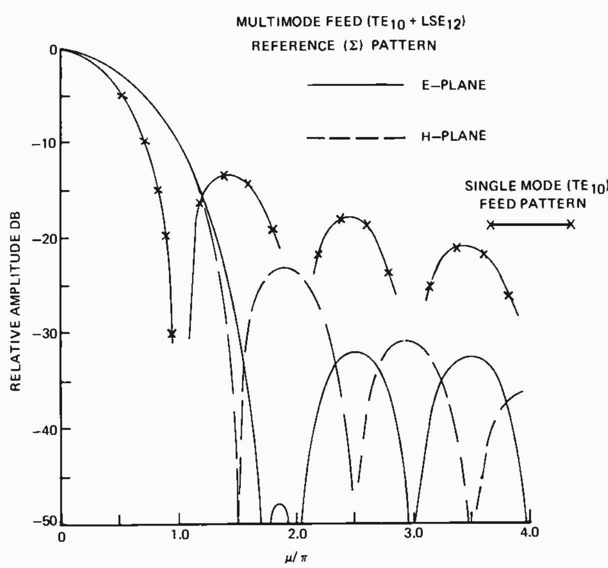


Fig. 4a
The sum patterns are compared with the fundamental mode (TE_{10}) pattern of a single horn to illustrate its lower beamwidth and higher sidelobe levels.

mathematically as

$$E_{REF}(x,y) = [1 + A_{21}\cos(2\pi y/a)]\cdot\cos(\pi x/a) \quad (1)$$
$$= 2A_{21}[T + \cos(2\pi y/a)]\cdot\cos(\pi x/a)$$
where $T = (1-A_{21})/A_{21}$

when the modes are co-phased. The distribution of E_{REF} is "cosine tapered" along the x-axis (H-plane) of the horn aperture and "cosine-squared-on-pedestal tapered" along the y-axis (E-plane), as illustrated in Fig. 3. The "cosine-squared-on-pedestal" amplitude tapering in the E-plane of the resultant distribution, which is the result of LSE_{12} mode incorporation, gives rise to the low-sidelobe and beamwidth equality (symmetry) property of dual-mode radiation. A_{21}, the ratio of LSE_{12} to TE_{10} mode amplitude, controls the E-plane beamwidth and sidelobe characteristics of the horn. For 10-dB beamwidth equality of E- and H-plane patterns, a typical design requirement for efficient illumination of a reflector antenna by a horn feed, A_{21} = 0.67.

The mathematical expression of the multimode-feed radiation-pattern function, for the reference-mode illumination characteristic of Eq. 1, is

$$g_{\Sigma}(u) = g_{10}(u) + A_{12}g_{12}(u) \quad (2)$$

where

$$g_{10} = \frac{\sin(u\sin\phi)}{u\sin\phi}\cdot\frac{\cos(u\cos\phi)}{(\pi/2)^2-(u\cos\phi)^2}$$

$$g_{12} = \frac{u\sin\phi\ \sin(u\sin\phi)}{\pi^2-(u\sin\phi)^2}\cdot\frac{\cos(u\cos\phi)}{(\pi/2)^2-(u\cos\phi)^2}$$

$u = (\pi a/\lambda)\sin\theta$
λ = wavelength
θ = angle measured from feed axis in the plane of pattern calculation
$\phi = \pi/2$ for E-plane, 0 for H-plane

Computed sum pattern functions of the multimode feed, with $A_{21} = 0.67$, are shown in Fig. 4a superimposed with the E-plane pattern function of the simpler single-mode feed. The E-plane beam broadening and sidelobe-level reduction afforded by the dual-mode technique are evident in this figure. Maximum E- and H-plane sidelobes (of the multimode feed patterns) are observed at levels of −30 dB and −23 dB respectively, relative to the pattern maximum. The 10-dB beamwidth equality and low sidelobe levels of the feed pattern produce nominally optimum illumination and spillover efficiencies for the Cassegrain reflector antenna, yielding an antenna gain that approaches the maximum available from a given aperture dimension. Reflector shaping techniques may be incorporated into the antenna design to obtain a further gain increase, but are beyond the scope of this paper. Well-designed multimode monopulse feeds are capable of providing Cassegrain reflector antenna reference efficiencies in the 55% to 65% range.

The monopulse radar tracking capability of the multimode feed derives from its ability to independently couple the monopulse comparator network difference ports to the TE_{20} and LSE_{11} waveguide modes in the multimode horn. The TE_{20} and LSE_{11} modes, whose transverse electric field configurations are also described mathematically and illustrated in Fig. 2, provide difference or monopulse error patterns along the principal x- (H-plane) and y-(E-plane) axes respectively. The H-plane difference-pattern function of the TE_{20} mode and E-plane difference-pattern functions of the LSE_{11} mode, which describe the feed error patterns, are:

$$g_{\Delta H}(u) = \sin u/(\pi^2 - u^2) \quad (3a)$$
$$g_{\Delta E}(u) = u\cos u/[(\pi/2)^2 - u^2] \quad (3b)$$

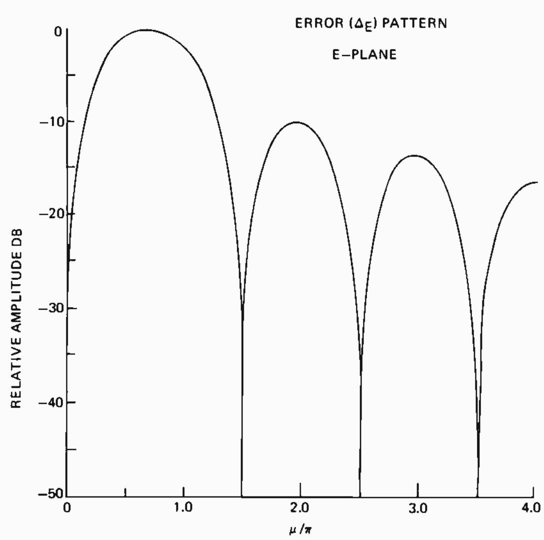


Fig. 4b
E-plane difference (monopulse error) pattern function for a multimode feed provides the radar tracking function in a single plane.

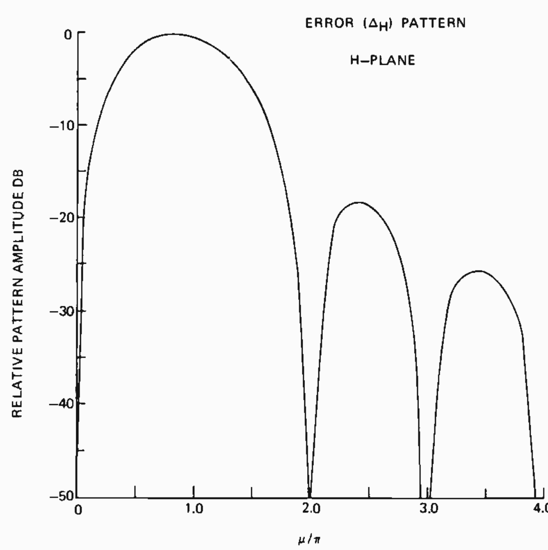


Fig. 4c
H-plane difference (monopulse error) pattern function provides the radar tracking function in a second, orthogonal plane.

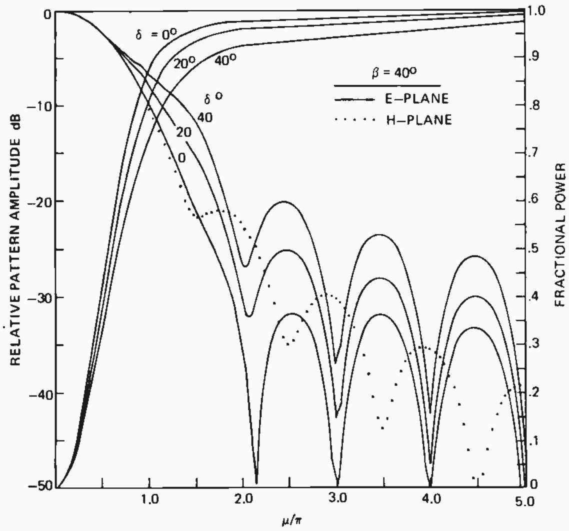


Fig. 5
Computed patterns illustrate the effects of mode phase error (δ) and horn flare angle phase error (β) on the E-plane sum patterns of the multimode feed. Note the increasing beamwidth and sidelobe levels accompanying these phase errors.

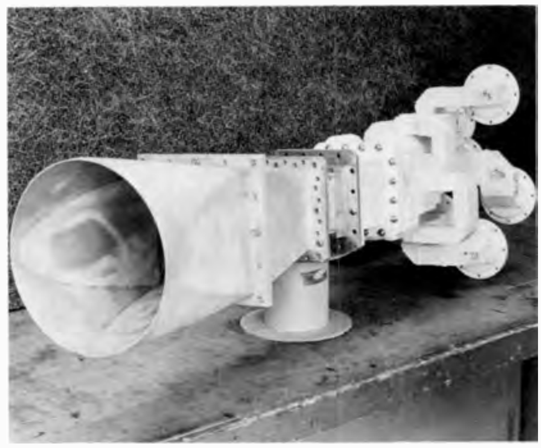


Fig. 6
RCA MSR's first high-performance multimode monopulse feed was developed for the Apollo Ships Instrumentation Radar (ASIR). This feed operated over a nominal 5.4 to 5.9 GHz frequency band.

Computed E- and H-plane difference-pattern functions of the multimode feed are illustrated in Figs. 4b and 4c, and together with the reference patterns complete the monopulse pattern set.

Antenna efficiencies associated with the difference patterns, which directly affect radar tracking sensitivity, are better for the multimode feed than for conventional four- and five-horn monopulse feeds.

This improvement is the result of a reduced difference-mode spillover loss characteristic afforded by the rotationally symmetric, low-sidelobe reference illuminations, permitting an increased angle intercept of feed radiation by the Cassegrain subreflector.

The previous multimode analysis assumed a "co-phase" condition between the TE_{10} and LSE_{12} reference modes. Since these modes do not constitute a degenerate pair (i.e., propogate with the same phase velocity), this condition will exist at only a single frequency. The relative phase shift between these modes, which is introduced by the waveguide feed structure, is a function of frequency and is the major parameter that determines the useful bandwidth of the multimode feed. Increased bandwidth is obtained with minimum relative phase difference of the TE_{10} and LSE_{12} modes, introduced by the section of feed between the mode generator and horn aperture. Feed designs requiring a 2π-radian phase shift between TE_{10} and LSE_{12} modes have been developed, and provide up to 10% useful bandwidth capability. Increased bandwidth capabilities in excess of 10% have been realized with feeds requiring a phase shift of only π radians between reference modes.

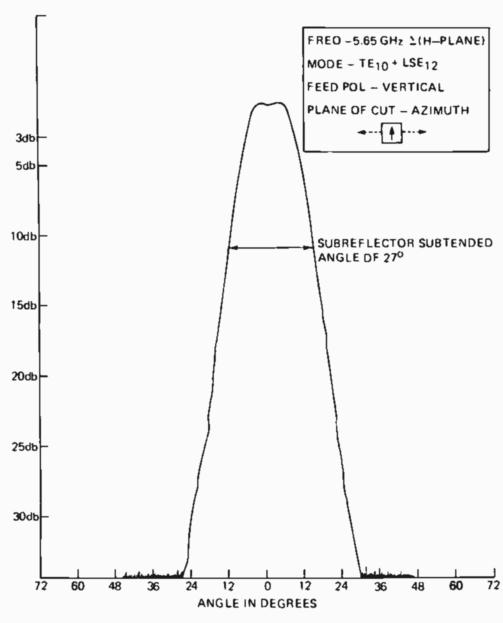
A second parameter influencing the performance capability of the multimode feed is the flare angle of the waveguide horn.

This flare angle imparts a nominal quadratic phase distribution to the transverse modal aperture illumination function, and degrades the low-sidelobe characteristics of the feed. The effect of phase difference between the TE_{10} and LSE_{12} modes at the horn aperture and the quadratic phase distribution produced by the horn flare angle are illustrated in the computed E- and H-plane reference-pattern data of Fig. 5. This data illustrates the E- and H-plane pattern functions of a square-aperture horn with dual-mode sum illumination, where a relative-mode phase difference and quadratic phase distribution are assumed.[8] The fractional power distribution of the complex pattern is superimposed on this data so that the fractional power content of any angular portion of the feed pattern can be determined or the feed spillover losses can be estimated. Data shown in Fig. 5 assumes a relative phase difference between modes of 0°, 20°, and 40°, coupled with a maximum quadratic phase error of 40°, introduced by the horn flare angle. The variation of E- and H-plane pattern beamwidths and degradation of E-plane sidelobe levels attributable to these effects are evident in the figure. A rule of thumb for high-performance multimode feed designs restricts the maximum-mode phase error to ±10° over the operational bandwidth, with a maximum quadratic phase error due to horn flaring of less than 50°.

Multimode feed developments at MSR

The first of the high-performance multimode monopulse feeds for Cassegrain antennas developed at MSR was the ASIR (Apollo Ships Instrumentation Radar) feed.

This feed, shown in Fig. 6, was designed for operation over the 5.4- to 5.9-GHz radar



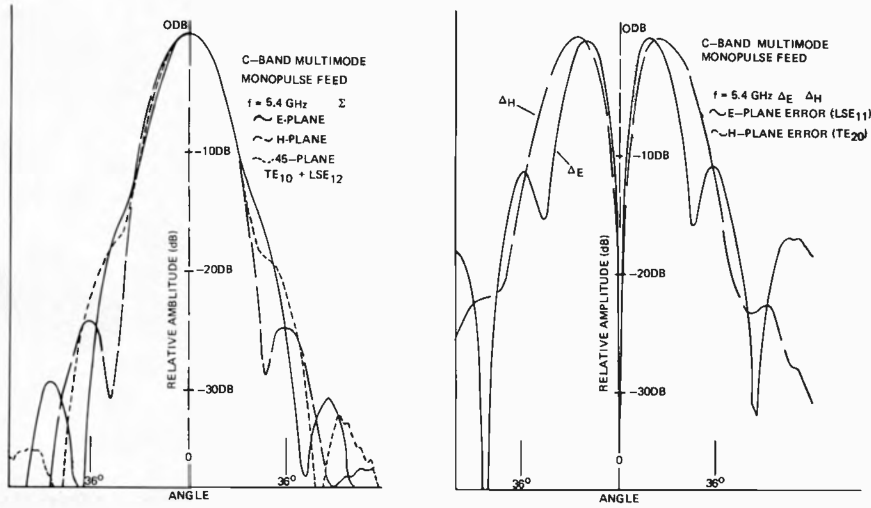


Fig. 7
Measured sum and difference patterns of the ASIR multimode monopulse feed.

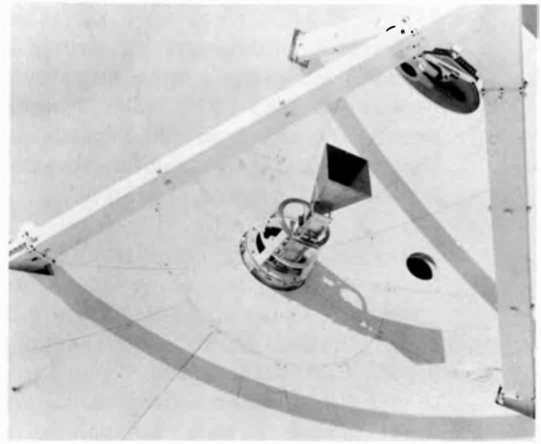


Fig. 8
Near-field multimode monopulse feed installed in a 29-foot diameter Cassegrain antenna. Operating frequency range was nominally 5.4 to 5.9 GHz.

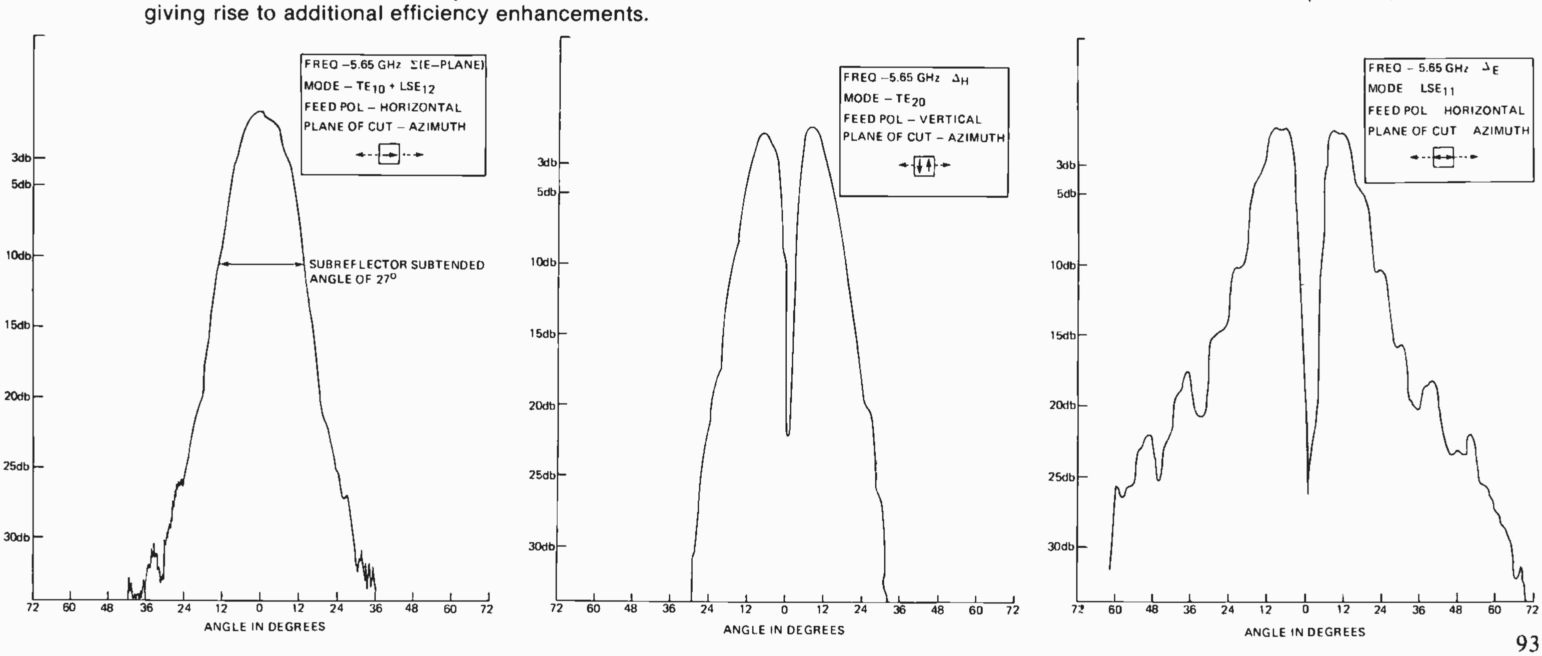
band, and was subsequently used in 16- and 12-ft-diameter Cassegrain reflector antenna systems. The feed employed a circular-aperture horn to obtain additional pattern improvements. Measured sum and difference patterns obtained from the feed, shown in Fig. 7 demonstrate the low-sidelobe reference-pattern available with multimode techniques. The antenna efficiency, determined by analysis of feed radiation pattern data and later verified by gain measurements on the antenna configuration, was nominally 60 to 65%.

A subsequent feed development at RCA MSR combined the advantages of multimode excitation and near-field horn radiation properties to achieve a further improvement of Cassegrain antenna efficiency.[9] The near-field multimode, monopulse feed employed the mode-generating network of the multimode feed in an electrically large pyramidal horn, and produced reference patterns that were essentially free of sidelobes. Spillover efficiencies obtained from this feed were thereby increased relative to the previous multimode feed. Although only useful in large Cassegrain reflector antenna configurations,[10] this marriage of techniques produced antenna efficiencies greater than 70%. Fig. 8 is a photograph of the near-field, multimode monopulse feed in a 29-ft.-diameter FPQ-6 Cassegrain reflector configuration. Measured monopulse feed pattern data is shown in Fig. 9, illustrating the improved low-sidelobe reference-pattern characteristics obtained.

Recent multimode, monopulse feed developments at MSR have addressed increased bandwidth capabilities and reducing the cross-polarization crosstalk problems inherent in all monopulse feeds.

A K_u-band multimode monopulse feed for a small Cassegrain antenna has been developed that permits operation over a

Fig. 9
Measured sum and difference patterns of the near-field feed. Note the virtual absence of sidelobes in the sum feed patterns, giving rise to additional efficiency enhancements.



14.7- to 15.6-GHz frequency band.[11] This feed uses a mode-generation technique requiring a π-radian relative phase shift between TE_{10} and LSE_{12} modes, thereby deriving the wide bandwidth capabilities. Fig. 10 is a photograph of this feed in a 26-in.-diameter Cassegrain geometry.

The mode-generating technique developed for the described feed above was incorporated in a K_a-band (34.5 - 35.5 GHz) feed design because of its attractive low-depolarization characteristic. This feed was combined with other selective mode-tuning devices to produce a multimode monopulse feed system with significantly reduced difference-channel, cross-plane depolarization. Using this design has reduced difference-channel depolarization by greater than 10 dB.

Fig. 10
A new wideband multimode monopulse feed for a small Cassegrain antenna. The new mode-generating technique has doubled bandwidth capabilities.

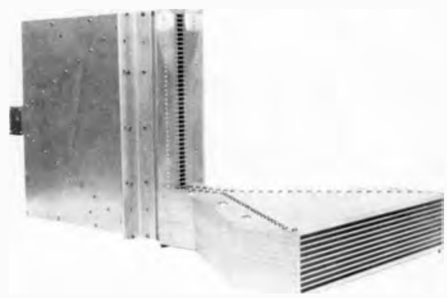


Fig. 11
Dual-mode sectoral horn power divider for a single-plane-scanned, low-sidelobe phased array. The low-loss "optical divider" properties of this horn make it attractive for millimeter-wave array applications.

Several unique array-feed concepts have been demonstrated and developed at MSR using the low-sidelobe properties of the dual-mode illumination characteristic.

A millimeter-wave planar-array configuration, developed by MSR under contract to NASA, employed a dual-mode E-plane sectoral horn as a constrained power divider.[5,6] This power divider, which is shown feeding a portion of the array in Fig. 11, was incorporated with a 50-element linear array of H-plane sectoral horn elements. The result was a low-loss, low-sidelobe planar phased array with wide-angle, single-plane electronic scan capabilities. Power division was accomplished by terminating the continuous aperture of the dual-mode, E-plane sectoral horn with a linear E-plane array of waveguide elements. These elements fed, in turn, phase shifters and the H-plane sectoral horn radiating elements of the array.

An experimental model of the complete array is shown under test conditions in Fig. 12. The phased-array model was designed to operate over a 15.2- to 16.8-GHz frequency band with a ±60° E-plane scan capability. Principal-plane pattern data obtained from this antenna for a 0° and 40° scanned beam is shown in Fig. 13. The dual-mode technique produced broadside E-plane array patterns at 16.0 GHz with maximum sidelobes below −28 dB. H-plane patterns of the array at this frequency were characterized by a maximum sidelobe of −39 dB. Pattern characteristics were nominally equivalent over the full design bandwith.

Sidelobe deterioration with scan angle is an intrinsic property of planar arrays; hence, the 40° E-plane scan patterns exhibited a somewhat increased maximum sidelobe level. Although not specifically developed for a radar application, the addition of a monopulse tracking capability to this array was demonstrated by generating a difference mode within the E-plane sectoral horn power divider and measuring the resulting array difference patterns.

A second array application of dual-mode power division techniques was realized at MSR by using a dual-mode radial waveguide power divider as a feed for a circular array antenna.[7] An X-band (7.9-8.5 GHz) model of a dual-mode, radial-waveguide, 16-way power divider is shown in Fig. 14, and an experimental model of a 64-element circular array antenna employing the power divider is shown in Fig. 15. Radiation patterns of this array demonstrated maximum sidelobes of −23 dB.[12] A monopulse tracking capability is also available for radar application of the circular array by using an orthogonal radial waveguide mode of the already available dual-mode set.

Conclusions

The low-sidelobe properties of dual or multimode illumination functions characterizing several waveguide types have been applied by MSR to a variety of antenna applications. The most widely used application of multimode technology has been for the design of high-performance monopulse feed systems for Cassegrain antennas. The combination of multimode and near-field radiation properties of horn feeds has resulted in further feed performance improvements. Wideband applications of multimode techniques have been demonstrated by minimizing the differential reference-mode

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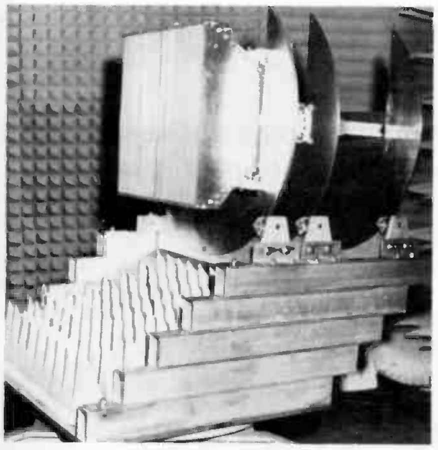

Fig. 12
Low-sidelobe phased array with dual-mode horn power divider undergoing testing in an MSR anechoic chamber.

phase shift introduced by the feed system. These newer mode-generation techniques have led to monopulse feed designs with significantly reduced difference-channel, cross-plane depolarization.

The application of dual-mode, low-sidelobe illumination techniques has also been extended to use with planar and circular arrays. Most noteworthy performance has been obtained from a planar-array antenna using multimode sectoral-horn power-divider techniques. This array provided wideband, low-sidelobe antenna-pattern characteristics with a single-plane ±60° electronic scan capability.

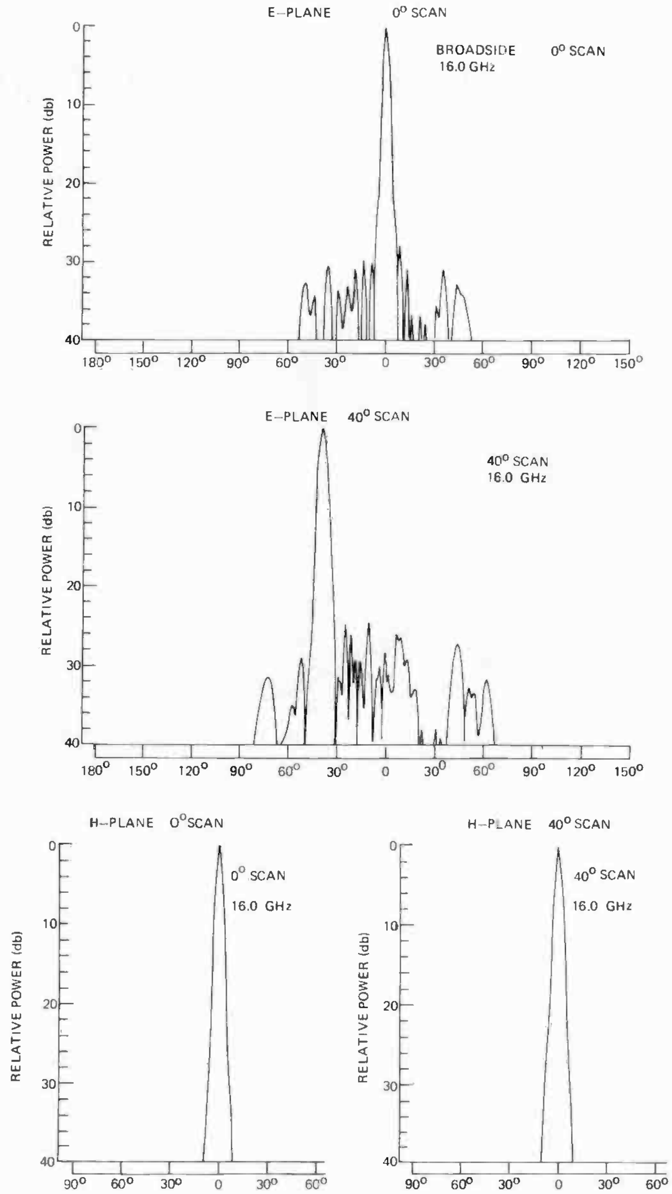

Fig. 13
E-(scan plane) and H-plane patterns of the low-sidelobe phased array with dual-mode sectoral horn power divider.

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Fig. 14
Low-loss dual-mode radial waveguide power divider for feeding a circular cylindrical array antenna.

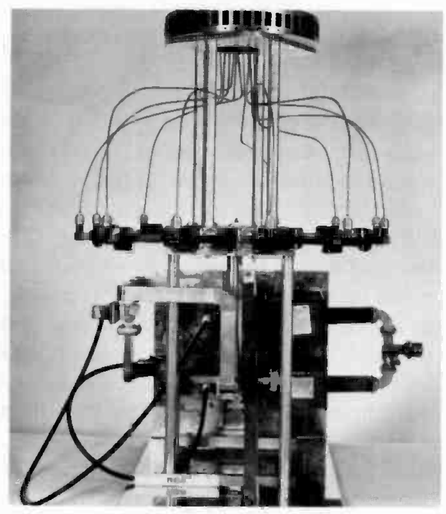

Fig. 15
X-band model of a circular array antenna with the radial waveguide dual-mode power divider. This configuration is capable of producing a beam that can be scanned 360° in a single plane.

on the job/off the job

Electronic speed control for model railroad realism

W.S. Pike

Electronic speed control of miniature locomotives enables this hobbyist to simulate realistic operation of his trains.

The N-gauge Susquehanna Southern Railway exists principally for the purpose of hauling coal from the mines in the mountains above the headwaters of the Susquehanna River to the port city of Susquehanna. Although coal traffic is the line's major source of revenue, passenger service has recently been expanded to cope with the increasing number of tourists attracted to this picturesque region.

Why electronic speed control?

In the initial stages of the railroad's existence, locomotive speed was controlled by using a conventional variable series resistance controller. This type of controller, as most model railroaders know, is not very satisfactory, leading to "jack-rabbit" starts, unrealistically abrupt stops, and difficulties in slow-speed running. One of the solutions to the problem is to use unidirectional pulses of variable duty cycle rather than dc for traction power. However, this tends to make the tiny permanent-magnet motors in the engine run hot, so that many variable-duty-cycle controllers also incorporate provision for either automatic or manual switchover to dc running. Our throttle is of the latter variety.

It is also desirable to incorporate an "inertia" circuit to simulate the "coasting" of real trains. This may be done with a diode and capacitor, which delays the fall of track voltage when the throttle is closed. Often a "brake" control is added, comprising one or more resistors which can be switched across the "inertia" capacitor to increase its rate of discharge. We have found it prudent also to include a "panic" button which short circuits the inertia capacitor so that a quick stop can be achieved in the event of imminent catastrophic collision.

Throttle operation

Fig. 1 depicts the Susquehanna Southern Railway control panel on which the throttle circuit is mounted. The throttle controls are at the edges of the panel. Also on the panel is the mimic diagram of the trackage. The duplicate throttle system permits each block of the layout to be powered from either throttle to permit simultaneous operation of two trains.

The large knob labeled SEL and BRAKE controls the various operating modes of the throttle. In the extreme counter-clockwise position, labeled "pulse," pulses of approximately 12 V amplitude at a 100-Hz repetition rate are applied to the tracks. As the THROTTLE knob at the top is advanced clockwise, the duty cycle of the pulses changes smoothly from 5% on and 95% off to 95% on and 5% off. The average dc value of this waveform thus changes from about 0.6 V to about 11.4 V. This range of control will permit extremely smooth starting of most N-gauge locomotives. They may also be made to inch along the track (if the track and wheels are clean) at one or two scale miles per hour or run up to any desired fraction of full speed.

No inertia is provided in the pulse mode of operation as it is advantageous (though less challenging to the operator) for

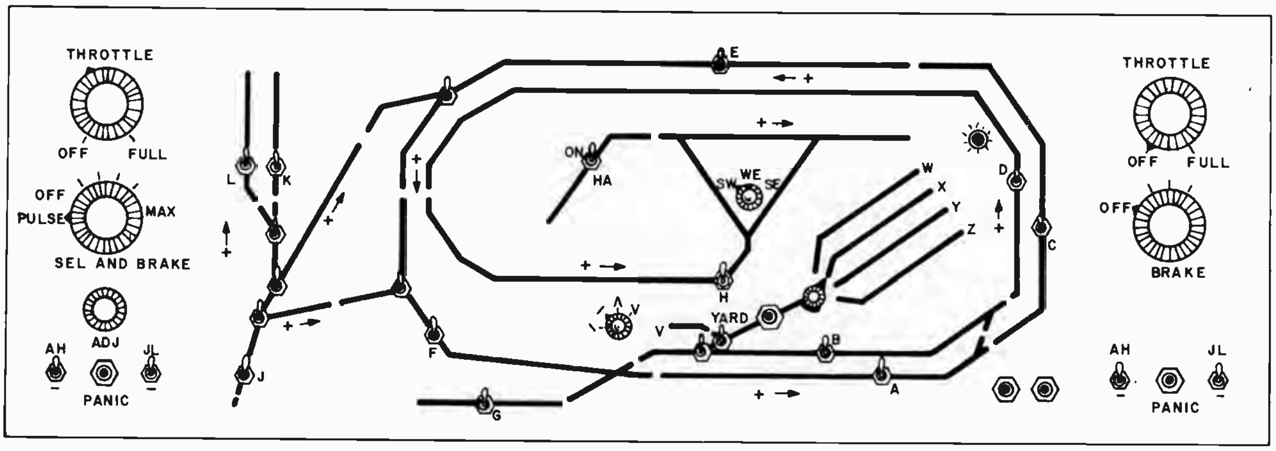

Fig. 1
Control panel of Susquehanna Southern Railway. Dual throttle control system permits simultaneous powering of two trains. Route selection and power switching of trains is accomplished by toggle and modified rotary switches.

some critical switching moves to have one throttle mode without inertia.

Moving the SEL and BRAKE knob to the next position changes over to dc operation with inertia. Thus a train may be started on pulse power and then changed over at any time to dc running. In the dc position, most of the Susquehanna Southern Railway's motive power will permit a locomotive to coast about three-fourths of a scale mile when unloaded and somewhat less when hauling a train. Braking action is available in five steps by advancing the SEL and BRAKE knob further clockwise. The PANIC button may be seen at the bottom of the panel between a pair of reversing switches.

Win Pike joined RCA Laboratories in 1946. The recipient of five RCA Laboratories Achievement Awards, he has worked on a variety of projects including reading machines for the blind, standard and special-purpose television cameras and receivers, equipment for automatic driving, and solid-state sensors. In addition to building model railroads for a hobby, he also works on pipe and electronic organs.

Contact him at:
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Ext. 2638

Throttle circuit theory

Although there are many fine published circuits for accomplishing all this, the engineering department of the Susquehanna Southern Railway decided to design its own throttle circuit. A block diagram of the result is shown in Fig. 2. A COS/MOS CD4047 integrated circuit wired as an astable multivibrator clocks the entire system at about 100 Hz. This is followed by a second CD4047 connected as a one-shot multivibrator. The THROTTLE knob adjusts the pulse width of the one shot within the limits previously described. In the "pulse" position of the mode selector

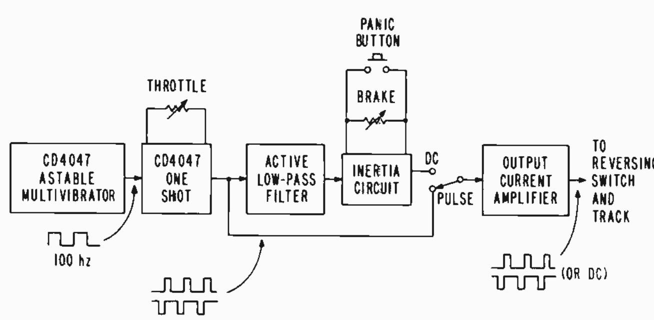

Fig. 2
An advantage of the author's throttle circuit design is that the same throttle potentiometer can be used for either dc or pulse operation without requiring complicated switching.

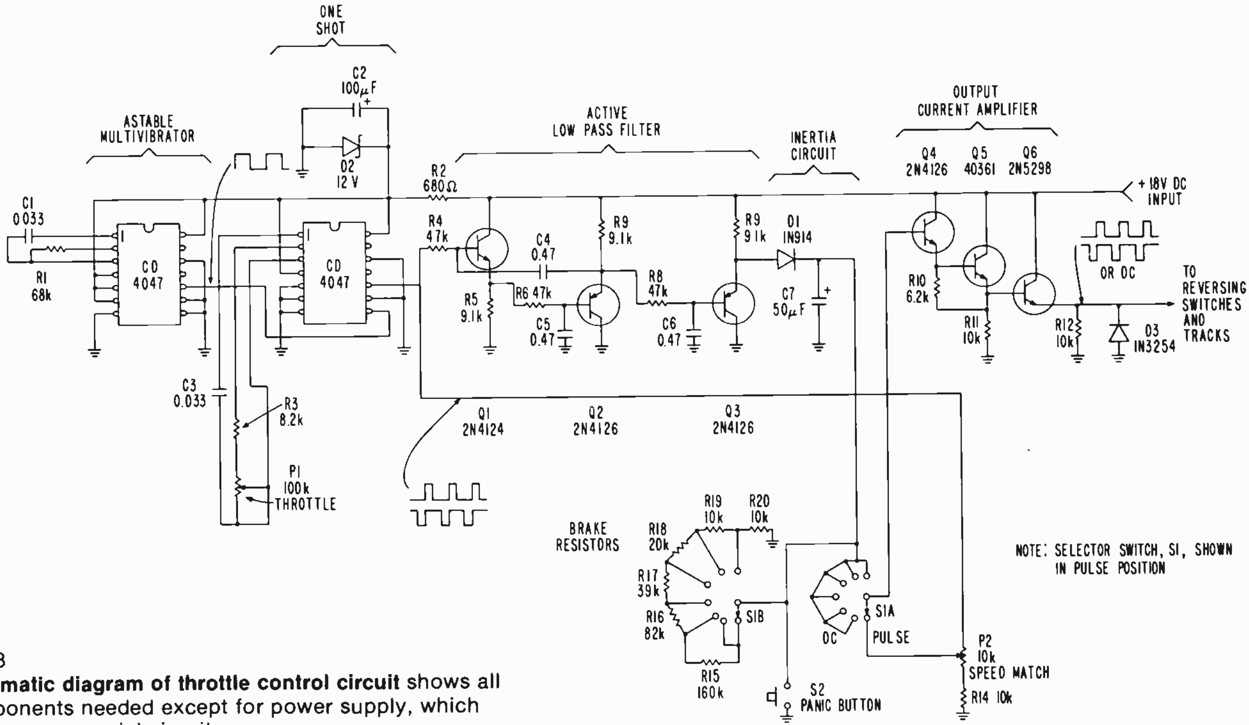

Fig. 3
Schematic diagram of throttle control circuit shows all components needed except for power supply, which requires no special circuitry.

control, the output of the one shot is applied without further processing via a Darlington current amplifier to the track. In the dc mode, an active low-pass filter with a turnover frequency of about 10 Hz (and a rate of cutoff of 18 dB/octave) and the diode/capacitor inertia circuit with its brake resistor are interposed between the one-shot and the current amplifier. The low-pass filter extracts the average dc value of the 100-Hz pulses and presents it to the output amplifier, thus permitting the same throttle potentiometer to be used for both dc and pulse operation without any switching complications. A reverse-biased diode is shunted across the output, mainly to protect the throttle circuitry from damage if a train happens inadvertently to enter a block already energized from the second throttle circuit and set for the opposite direction of travel (opposite polarity).

Throttle circuit design

The complete throttle control circuit is shown in Fig. 3. The CD4047 astable and monostable multivibrators require little comment. Potentiometer P1 is the throttle potentiometer controlling the pulse width of the monostable. Transistors Q1, Q2, and Q3 comprise the active low-pass filter, basically the well-known Sallen and Key configuration with one added RC section. Diode D1 and capacitor C7 comprise the "inertia" circuit, R15 through R20 are the braking resistors, and Q4, Q5, and Q6 comprise the Darlington-connected output current amplifier. Transistor Q6 is mounted on a heat sink. Diode D3 serves as the protective device.

Potentiometer P2 (visible in Fig. 1 just above the PANIC button and labeled ADJ), provides a means of adjusting the match between locomotive speed when running on pulse power and running on dc. It allows a limited adjustment of the pulse amplitude applied to the output amplifier. In practice, I have found that different locomotives sometimes require slightly different settings of this control to ensure a smooth mode transition from pulse to dc and vice versa.

If any reader chooses to duplicate this circuit, I should perhaps caution that depending on the tolerances of the timing components in the multivibrators, R3 and C3 may require tailoring to ensure that the one-shot varies smoothly from minimum to maximum duty cycle without entering a frequency-halving region at full throttle or ceasing operation at minimum throttle. Another possible modification would be to include "inertia" on opening the throttle. This may be done by adding resistance in series with D1.

I have not shown the details of the 18-V raw dc source which energizes the throttle circuit, as no special circuitry is required. Our supply comprises a transformer, bridge rectifier, and 5500-microfarad filter capacitor. Note, however, that the COS/MOS multivibrators are isolated from this supply by a resistor, R2, Zener diode, D2, and capacitor, C2.

The author will be glad to answer inquiries from anyone interested in duplicating this circuit, which has been in successful operation on the Susquehanna Southern Railway for over two years.

Reprint RE-23-5-18
Final manuscript received December 29, 1977.

Building control circuitry, collecting trains, and designing the track layout for an N-gauge system are just part of the fun for a model railroader. These views of the author's "Village of Gap" in the Susquehanna Valley show the realism in detail put into building the structures and scenery.

Ed. Note: Although the subject of this article is electronic speed control, model railroad buffs most certainly will want additional details on Win Pike's railroad system. The following gives some construction and operating particulars about his Lilliputian transportation network. *FJS*

The Susquehanna Southern Railroad, an N gauge (9 mm between running rails) model railroad is constructed entirely on a standard 36-inch wide, flush door. A sheet of Homasote is glued to the top surface of the door, and the raised portions of the railroad have been constructed by the "cookie cutter" method, raising and supporting the Homasote where necessary with glued-in wooden supports.

Scenery is made up of plaster on wire screen, again supported where necessary with wooden framing. Although this method of construction is not as flexible as open benchwork, it is simple to make and, particularly with N gauge, results in quite a lot of readily portable railroad in a small space.

The structures visible in the photographs are a mixture of commercial plastic model kits and scratch-built buildings. The backdrop (as yet unfinished) is in the process of being painted by the author's son, Eric Pike.

The trackage contains 16 separate blocks and 15 electrically operated track switches, including two double slip switches (to save space). All but two of these switches are commercial units using conventional, double-coil mechanisms. The remaining two, which are more satisfactory, are driven by "hook lever" type, single-coil mechanisms "liberated" from a defunct pipe organ. Because of their size, these mechanisms are concealed under the scenery.

Most of the wiring is simple; a double-throw, double-pole, center-off switch associated with each block permits powering it from either of the two power supplies. However, in a few areas, notably the upper level wye (visible in the center of the control panel) route selection and power switching have been combined into a single rotary switch which has been modified to include a coaxial pushbutton. One selects the desired route by rotating the switch, then pushing the button to align the track switches to the selected route. A similar system is used in the yard area of the railroad.

An extension running down the side wall of the room in which the railroad is housed is planned for a later date. This will connect on to the existing trackage and will probably require a second control panel.

Rolling stock comprises a mixture of European and American models and includes 2 diesel locototives, 2 steam locomotives, and 2 electric locomotives. In operation, most trains are kept fairly short because of the relatively sharp curves and the 4% gradient to the upper level.

The 1978 David Sarnoff Awards for Outstanding Technical Achievement

RCA's highest technical honors have been announced for 1978. Each award consists of a gold medal and bronze replica, a framed citation, and a cash prize.

Albert Feller

Advanced Technology Laboratory, Camden, N.J.

For outstanding achievement in the use of computer-aided design techniques for large scale integrated circuits.

Feller

At a 1977 IEEE workshop on the use of computer-aided design approaches, it was indicated that RCA's system for LSI design is the most advanced in the industry. Al Feller is the prime contributor to this advanced position. His work in the development of computer-aided standard-cell LSI array design and technology resulted in the development of advanced signal-processing equipment for RCA communication and radar systems. These same design approaches have also allowed cost-effective development of semiconductor products. He made specific contributions to: APAR, the automatic placement and routing program for CMOS standard-cell arrays; the SUMC-DV computer for NASA, in CMOS and CMOS/SOS form; an automotive on-board processor; the multiport two-dimensional placement and routing program; the ATMAC microprocessor; and radiation-hardened CMOS/SOS standard-cell LSI arrays.

Adam

Aires

Clark

Davis

Gorski

Katagi

Sasaki

Kenneth C. Adam | Ramon H. Aires | Charles A. Clark, Jr. | William J. Davis | John C. Gorski | Kazuo Katagi | Akira Sasaki

Avionics Systems, Van Nuys, Calif.

For outstanding technical achievement in the development of airborne color weather radar indicators.

RCA's PriMUS-90 and -400 ColoRadar units were industry's first airborne weather radars to use color indicators. The new designs also provide four times the resolution of previous digital-memory-refreshed indicators, and allowed the use of a standard color crt by converting the radar scan from polar coordinates to x-y (tv-style) scan. The design team worked very quickly; RCA was thus able to announce color radar availability significantly ahead of the competition and even go to production ahead of schedule. Customer acceptance for the color-indicator radars has been above expectation, so much so that production schedules had to be accelerated twice during the first nine months after announcement.

David W. Luz|James A. McDonald|John C. Peer

Consumer Electronics Division, Indianapolis, Ind.

For outstanding team achievement in the development of scan and power supply systems for color television.

All of the color-tv sets now being manufactured by Consumer Electronics enjoy the benefits of this team's design effort: better power efficiency; substantially lower cost; and improved scan and high-voltage performance. These benefits come from combining the functions of horizontal deflection and power supply regulation. A weighted average of power consumption for the "XtendedLife" models is 92 W; the immediately preceding line had a weighted power average of about 135 W. The improved efficiency and reduced power consumption are expected to contribute substantially to the reliability and life-cycle savings of the "XtendedLife" sets. Improved performance results from the excellent scan stability, which is independent of line and load variations. RCA's "XtendedLife" XL-100 and ColorTrak receivers, which use the new design, have been successful in terms of sales and reliability.

Luz

McDonald

Peer

Fernand F. Martin|Samuel Waldstein|Jason H. Woodward

Automated Systems, Burlington, Mass.

For excellence of team effort in the product development of a hand held laser rangefinder.

The AN/GVS-5 laser rangefinder is as much as ten times improved over previous rangefinder designs in terms of weight, power consumption, and cost, while meeting or exceeding the operational characteristics of its predecessors. For example, the previous 25-lb. units cost $30,000 apiece to produce, but the 5-lb. AN/GVS-5 is producible for under $4,000. Army users can now determine the range to targets instantly, and can make up to seven hundred 10,000-meter range measurements with one charge of the self-contained 8-oz. battery. The success of the rangefinder design (present orders total $30 million) is based in large part on the rangefinder's design-to-unit-cost program, which combined the efforts of the design and production teams to produce the best tradeoff among size, weight, power consumption, availability of parts and materials, and cost.

Martin

Waldstein

Woodward

Murray A. Polinsky|Otto H. Schade, Jr.

Solid State Division, Somerville, N.J.

For outstanding technical achievement in the development of high performance BiMOS integrated circuits.

BiMOS integrated circuits, which combine bipolar and MOS transistors on the same chip, are a unique development of the Solid State Division. The circuits have the outstanding performance characteristics of each type of transistor, and so have been very popular, with millions per year sold. The applications for BiMOS so far have included operational amplifiers, comparators, smoke detectors, and television digital tuning circuits. Murray Polinsky's process engineering work greatly simplified the method of fabricating the MOS and bipolar devices on the same chip, and Otto Schade had the prime responsibility for the circuit design.

Polinsky

Schade

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Dates and Deadlines

Upcoming meetings

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MAY 1-3, 1978—**Microwave Power Tube Conf.** (IEEE) Naval Postgraduate School, Monterey, CA **Prog Info:** Dr. George Caryotakis, Varian Assoc., 611 Hansen Way, Palo Alto, CA 94308

MAY 6-11, 1978—**American Ceramic Soc. 80th Annual Mtg. & Expo.** (ACS) Cobo Hall, Detroit, MI **Prog Info:** Frank P. Reid, Exec. Director, The American Ceramic Society, Inc., 65 Ceramic Drive, Columbus, OH 43214

MAY 10-12, 1978—**Conf. on Software Engrg.** (IEEE, NBS) Hyatt Regency Hotel, Atlanta, GA **Prog Info:** Harry Hayman, Conf. on Software Engrg., PO Box 639, Silver Spring, MD 20901

MAY 15-19, 1978—**Intl. IEEE/AP Symp. & USNC/URSI Mtg.,** (IEEE, AP, USNC/URSI) Adult Education Ctr., Univ. of MD, College Park, MD **Prog Info:** G. Hyde, Room 2146, Comsat Labs., Box 115, Clarksburg, MD 20734

MAY 16-18, 1978—**NAECON (National Aerospace & Electronics Conf.)** (IEEE) Dayton Convention Ctr., Dayton, OH **Prog Info:** NAECON, 140 E. Mounument Ave., Dayton, OH 45402

MAY 17-19, 1978—**Circuits & Systems Intl. Symp.** (IEEE) Roosevelt Hotel, New York, NY **Prog Info:** H.E. Meadows, Dept of Elec. Engineering & Computer Science, Columbia Univ., New York, NY 10027

MAY 18, 1978—**Trends & Applications: Distributed Processing** (IEEE, NBS) Natl. Bureau of Standards Conv. Ctr., Gaithersburg, MD **Prog Info:** Ms. Helen Wood, NBS, Bldg. 225 B 212, Washington, DC 20234

MAY 23-25, 1978—**Electro/78** (IEEE) Boston-Sheraton, Hynes Auditorium, Boston, MA **Prog Infor:** W.C. Weber, Jr., IEEE Electro, 31 Channing St., Newton MA 02158

MAY 29-JUN 1, 1978—**Intl. Quantum Electric Conf. (10th)** (IEEE) Atlanta, GA **Prog Info:** Joseph Giordmaine, Bell Labs, 600 Mountain Ave., Murray Hill, NJ 07974

JUN 4-7, 1978—**Intl. Conf. on Communications** (IEEE, et al) Sheraton Hotel, Toronto, Ont. **Prog Info:** F.J. Heath, Power System Operation Dept., Ontario Hydro Electric Power System, 700 Univ. Ave., Toronto, Ont.

JUN 5-8, 1978—**Natl. Computer Conf.** (AFIPS, IEEE, ACM) Anaheim Conv. Ctr., Disneyland Hotel Comp., Anaheim, CA **Prog Info:** Stephen Miller, SRI Intl., ISE Division, Menlo Park, CA 94025

JUN 5-8, 1978—**13th Photovoltaic Spec. Conf.** (IEEE) Shoreham Americana Hotel, Washington, DC **Prog Info:** John Goldsmith, M/S 169/422, JPL, 4800 Oak Grove Dr., Pasadena, CA 91103

JUN 12-13, 1978—**Microcomputer Based Instrumentation** (IEEE) Natl. Bureau of Standards Conf. Facil., Gaithersburg, MD **Prog Info:** Bradford Smith, A-130 Technology, Natl. Bureau of Standards, Washington, DC 20234

JUN 13-15. 1978—**Power Electronics Specialist Conf.** (IEEE) Syracuse, NY **Prog Info:** F.B. Goldin, Mail Drop 30, General Electric, Genessee Street, Auburn, NY 13021

JUN 19-21, 1978—**Design Automation** (IEEE) Caesar's Palace, Las Vegas, NV **Prog Info:** S.A. Szygenda, Univ. of Texas at Austin, Dept. of Elect. Engr., Austin, TX 78712

JUN 20-22, 1978—**Pulsed Power Modulator Conf.** (IEEE) Statler Hilton, Buffalo, NY **Prog Info:** Sol Schneider, U.S. Army, ERADCOM, Code DREL-TL-BG, Fort Monmouth, NJ 07703

JUN 21-23, 1978—**Machine Processing of Remotely Sensed Data** (IEEE) West Lafayette, IN **Prog Info:** D. Morrison, Purdue Univ. LARS, 1220 Potter Drive, West Lafayette, IN 47906

JUN 26-28, 1978—**Device Research Conf.** (IEEE) Univ. of Calif., Santa Barbara, CA **Prog Info:** Dr. James McGroddy, IBM, T.J. Watson Research Ctr., Yorktown Heights, NY 10598

JUN 26-29, 1978—**Conf. on Precision Electromagnetic Measure** (IEEE, NBS, URSI/USNC) Conf. Ctr., Ottawa, Ont. **Prog Info:** Dr. Andrew F. Dunn, Natl. Research Council, Montreal Road, Ottawa, Ont.

JUN 27-29, 1978—**Intl. Microwave Symp.** (IEEE, et al) Chateau Laurier, Ottawa, Ont. **Prog Info:** A.L. VanKoughnett, Communications Research Ctr., POB 11490, Station H, Ottawa, Ont. K2H 8S2

JUL 18-21, 1978—**Nuclear & Space Radiation Effects** (IEEE) Univ. of New Mexico, Albuquerque, NM **Prog Info:** B.L. Gregory, Sandia Labs., Dept. 2140, Albuquerque, NM 87115

AUG 20-25, 1978—**Intersociety Energy Conversion Engr. Conf.** (IEEE) Town & Country Hotel, San Diego, CA **Prog Info:** George P. Townsend, Hamilton Standard Div., United Technologies Corp., Windsor Locks, CT 06096

AUG 22-25, 1978—**Intl. Conf. on Parallel Processing** (IEEE) Shanty Creek Lodge, Bellaire, MI **Prog Info:** Prof. T.Y. Feng, Dept. of Elect. & Comp. Engr., Wayne State University, Detroit, MI 48202

SEP 5-8, 1978—**COMPCON FALL** (IEEE) Washington, DC **Prog Info:** COMPCON FALL, P.O. Box 639, Silver Spring, MD 20901

SEP 6-8, 1978—**Intl. Optical Computing Conf.** (IEEE) Imperial College, London, Eng. **Prog Info:** S. Horvitz, Box 274, Waterford, CT 06385

Calls for papers

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JUN 13-15, 1978—**Automated Testing for Electronics Mfg.** (ATE) Boston Park Plaza Hotel, Boston, MA **Deadline Info: ab. 200-500 wds. and short biog. to:** Sheila Goggin, ATE Seminar/Exhibit Coordinator, Circuits Mfg. Magazine, 1050 Commonwealth Ave., Boston, MA 02215

OCT 9-11, 1978—**Semiconductor Laser Conf. (6th)** (IEEE) Hyatt Regency Hotel, San Francisco, CA **Deadline Info: 6/15/78 to** T.L. Paoli, Bell Laboratories, 600 Mountain Ave., Murray Hill, NJ 07974

OCT 11-12, 1978—**3rd Specialist Conf. on Tech. of Electroluminescent Diodes** (IEEE) Hyatt Regency Hotel, San Francisco, CA **Deadline Info: 6/15/78 to** R.N. Bhargava, Phillips Lab., Briarcliff Manor, NY 10510

NOV 7-9, 1978—**PLANS '78 (Position Location & Navigation Symp.)** (IEEE) San Diego, CA **Deadline Info: 5/15/78 to** Nelson Harnois, Cubic, PO Box 80787, San Diego, CA 92138

DEC 4-6, 1978—**Natl. Telecommunications Conf.** (IEEE) Hyatt Hotel, Birmingham, AL **Deadline Info: 5/78 to** H.T. Uthlaut, Jr., South Central Bell, PO Box 771, Birmingham, AL 35201

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Automated Systems

D.R. Bartlett
The YAH-64 ATE support program—Autotestcon '77, Hyannis, MA (11/2-4/77)

H.L. Fischer|R.E. Hanson
New techniques for automated engine diagnostics—an update—Autotestcon '77, Hyannis, MA (11/3/77)

E.B. Galton
Welcoming address and introduction—Autotestcon '77 Hyannis, MA (11/2/77)

J.I. Herzlinger
The use of commercial equipment in military mobile systems—Mobile Electronics Systems Packaging Symp., Boxborough, MA (11/2/77)

Advanced Technology Laboratories

E. Hutto
Emile Berliner, Eldridge Johnson and the Victor Talking Machine Company—*J. Audio Engineering Soc.*, Centennial Issue, Vol. 25, No. 10/11 (Oct/Nov 77) pp. 666-73

R. Kenville|G.J. Ammon|C.W. Reno
Optical video disc for high rate digital data recording—Electro-Optics/Laser Conf. and Expo., Anaheim, CA (10/25/77)

W. Thomas
Industry views of government specifications and standards—Defense Specifications Management Course, Army Logistics Management Center, Ft. Lee, VA (12/8/77)

Globcom

M.E. Logiadis
International field tests of digital facsimile equipment—CCITT, Study Group XIV, Geneva (11/14-18/77)

Government Communications Systems

M. Nguyen|R. Pickholtz
Bounds for the queue in loop system—1977 Intl. Mtg. Data Transmission, Liege, Belgium (11/14/77)

S. Yankelewitz
High density tape recording—Drexel University, Philadelphia, PA (12/5/77)

Laboratories

C.R. Carlson
Thresholds for perceived image sharpness—*Proc.*, SPSA Conf., Rochester, NY (10/24/77) pp. 76-80

R. Dawson|J. Preisig
J. Carnes|J. Pridgen
A CMOS buried-N-channel CCD compatible process for analog signal processing applications—*RCA Review*, Vol. 28, No. 3 (9/77) pp. 406-435

C.A. Deckert
Etching of CVD Si_3N_4 in acidic fluoride media—Electrochemical Soc. Mtg., Phila., PA (5/8-13/77)

R.E. Enstrom|D.A. Doane
A finite element solution for stress and deflection of a centrally loaded silicon wafer—The Electrochemical Soc., Seattle, WA (5/21-26/77)

K.G. Hernqvist
Continuous laser oscillation at 2703 angstroms in copper ion—*IEEE J. Quantum Electronics*, Vol. QE-13, No. 11 (11/17) p. 929

K.G. Hernqvist
Long-life hollow cathode laser—*IEEE J. of Quantum Electronics*, Vol. QE-14, No. 2 (2/78) pp. 129-132

M.L. Hitchman
Analysis of equilibrium potentials of hydrogen tungsten bronzes—*J. of Electroanalytical Chemistry*, Vol. 85 (1977) pp. 135-44

P.J. Zanzucchi|D.E. Carlson
Optical properties of discharge-produced a-Si—Electrochem. Soc. Meeting, Atlanta, GA (10/9-14/77)

P.J. Zanzucchi|M.T. Duffy|R.C. Alig
Optical reflectance method for determining the surface quality of sapphire (Al_20_3)—*J. Electrochemical Soc.*, Vol. 125, No. 2 (1978) p. 299

P.J. Zanzucchi|C.R. Wronski|D.E. Carlson
Optical and photoconductive properties of discharge-produced amorphous silicon—*J. Appl. Phys.*, Vol. 40, No. 12 (1977) p. 5227

Missile and Surface Radar

R. J. Bannister|H. B. Boardman
M. D. Brazet
ORTS—A shipboard automatic test system
Proc., Autotestcon '77, Hyannis, MA (11/2-4/77)

J.A. Bauer
Leadless carrier applications for avionics packaging—Digital Avionics System Conf., Los Angeles, CA (11/2-4/77)

J.A. Bauer
The use of chip carriers for high packaging density, high reliability, high performance products—Workshop on the Impact of LSI on Contact Systems (11/77)

M.W. Buckley, Jr.
Project management—Education for Business and Industry, Ltd., London, England (11/1-2/77)

M.W. Buckley, Jr.
Project management—Seminar, Drexel Univ., Phila., Pa. (11/9-11/77 and 12/7-9/77)

R. DiFelice|J. Drenik
Mechanical design and integration of phased arrays naval sea systems command—*Proc.*, Mechanical Engineering in Radar Symp., Washington, DC (11/8-10/77) pp.230-35

B. Fell
Basic radar concepts: an introduction to radar for optical engineers—*Proc.* BMDATC (12/77)

W.A. Harmening
Static mass balancing with a torsion spring and four-bar linkage—*Proc.*, Mechanical Engineering in Radar Symp., Washington, DC (11/8-10/77), pp. 169-72

J.W. Hurley
Industrial logistics management—Phila. Chapter of the Soc. of Logistics Engineers (10-wk symp.) Philadelphia, PA (Oct-Dec 77)

P.R. Kalata
On system identification with and without certainty—*J. of Cybernetics*, Vol. 8, Issue 1 (Jan-Mar 1978) pp. 31-50

R.J. Kosich
AEGIS ship combat system distributed computer system design—WINCON '78, Sheraton-Universal Hotel, CA (2/15/78)

E.J. Nossen|E.R. Starner
One-way doppler extractor—*RCA Review*, Vol. 38, No. 4 (12/77)

R.P. Perry|L.W. Martinson
Radar matched filtering—Chapter in *Radar Technology*, Artech (10/77) pp. 163-69

S.A. Steele
Characteristics of managing real time solftware development for military systems—AIAA Computers in Aerospace Conf., Los Angeles, CA (11/1/77)

L. Weinberg
Scheduling multifunction radar systems—*Proc.*, IEEE Electronics and Aerospace Systems Conv. (12/77)

Patents

Astro-Electronics

L. Muhlfelder|J.E. Keigler|B. Stewart
Momentum biased active three-axis satellite attitude control system—4071211

R.J. Treadwell
Brushless phase locked servo drive—4072884

Automated Systems

R.F. Croce|G.T. Burton
Holographic high resolution contact printer—4043653 (assigned to U.S. government)

C.S. Warren
Data packets distribution loop—4071706

Avionics Systems

J.E. Miller
Multi-target tracker—4072943

J.R. Hall
Circuit for inhibition of autogenetic false alarms in a collision avoidance system—4076010

Broadcast Systems

L.J. Bazin
Signal comparator circuit—4069432

R.A. Dischert|R.N. Hurst|A.C. Luther, Jr.
Signal processor using charge-coupled devices—4074307

E.P. Herrmann
Four-quadrant multiplier—4071777

R.N. Hurst
Arrangements for testing color television systems—4069500

B.M. Pradal
Network for temperature compensation of an at cut quartz crystal oscillator—4072912

D.M. Schneider|L.J. Bazin
Constant pulse width sync regenerator—4064541

H.G. Seer, Jr.
Apparatus for automatic color balancing of color television signals—4064529

Consumer Electronics

D.J. Carlson
Remote control transmitter with an audible battery life indicator—4067000

M.N. Norman
Automatic beam current limiter—4067048

Commercial Communications Systems Div. Staff

L.P. Orchard
Food product extrusion apparatus and method—4068008

Government Communications Systems

W.A. Borgese
Apparatus for measuring a dimension of an object—4063820 (assigned to U.S. government)

M. Lysobey
Wide range frequency modulation of narrow loop bandwidth phase-locked oscillators—4074209 (assigned to U.S. Government)

L.P. Nahay
20Hz ringdown solid state two-wire/four-wire converter—4037065 (assigned to U.S. government)

Laboratories

C.H. Anderson
Flat panel display with beam injection cleanup—4069439

F. Aschwanden
SECAM identification circuit—4072983

D.E. Carlson
Semiconductor device having a body of amorphous silicon—4064521

J.M. Cartwright, Jr.
Current mirror amplifiers with programmable current gains—4064506

A.G. Dingwall
Method of making a semiconductor device—4069577

A.G. Dingwall|B.D. Rosenthal
Direct-coupled cascade amplifier with automatically adjusted quiescent output signal level—4068182

A.G. Dingwall|B.D. Rosenthal
Voltage controlled oscillator having equally controlled current source and current sink—4072910

A.H. Firester|J.P. Walentine
Defect plotting system—4069484

R.A. Geshner|L.J. Sciambi
Photomask dryer—4068390

W.G. Gibson
Delay line network for processing a composite electrical signal—4074308

A.C. Ipri
Silicon resistive device for integrated circuits—4072974

H.C. Johnson
Monotonically ranging fm-cw radar signal processor—4072947

G. Kaganowicz|J.W. Robinson
Video disc with a dielectric layer formed from styrene and nitrogen—4072985

P.J. Kannam
Transistor having improved junction breakdown protection integrated therein—4071852

H. Kressel|R.V. D'Aiello|P.H. Robinson
Polycrystalline or amorphous semiconductor photovoltaic device having improved collection efficiency—4070206 (RCA has title (waiver), NASA has license)

W.G. McGuffin
Adaptive delta modulation system—4071825

J.I. Pankove
Apparatus and method for maskless ion implantation—4074139

J.I. Pankove|D.E. Carlson
Electroluminescent semiconductor device having a body of amorphous silicon—4069492

H.L. Pinch|B. Abeles|J.I. Gittleman
Method of making high resistance cermet film—4071426

J.H. Reisner|W.H. Morewood|
G.H. Riddle
Electron beam disc recorder—4074313

W. Rosnowski|R. Denning
Method of fabricating a semiconductor device—4066485

J.M. Shaw|K.H. Zaininger
Method of manufacturing apertured aluminum oxide substrates—4069094 (assigned to U.S. government)

Mobile Communications

R.M. Kongelka
Releasable mounting system—4071217

Missile and Surface Radar

P.T. Patterson
System and method for authenticating an electronically transmitted document—4064389 (assigned to U.S. government)

Picture Tube Division

A.M. Morrell
Corrugated shadow mask assembly for a cathode ray tube—4072876

RCA Ltd., Canada

J.M. Keelty
Wide acquisition range MSK demodulator input circuit—4072905

A. Waksberg
Automatic optical bias control for light modulators—4071751

A. Waksberg
Retro-reflection communication system—4064434

Solid State Division

A.A. Ahmed
Current mirror amplifier—4068184

B. Crowle
Voltage regulators of a type using a common-base transistor amplifier in the collector-to-base feedback of the regulator transistor—4074181

N.F. Gubitose|L. Gawelko|R.J. Satriano
Method for cracking brittle material—4068788

R.C. Heuner|S.J. Niemiec
M.B. Goldman|G.I. Morton
Protection circuitry for insulated-gate field-effect transistor (IGFET) circuits—4066918

R.H. Isham, 2nd
Sawtooth voltage generator for constant amplitude sawtooth waveform from varying frequency control signal—4071776

J.R. Jasinski|J.B. Pickard|C.E. Doner
Double tuned input circuit for television transmitter amplifier—4070627

N. Kucharewski
Amplifier circuit—4069431

A.J. Leidich
Amplifier circuit—4064463

T.J. Robe
Input stage for fast-slewing amplifier—4074205

Microprocessor technology, electro-optics, and automotive electronics anthologies available

Three new comprehensive reprints that uniquely display RCA's current skills in microprocessors, electro-optics, and automotive electronics are now available. These reprints consist of selected papers from four of the most popular recent issues of the *RCA Engineer*. Only papers of current value are included.

Microprocessor technology offers 118 pages of general microprocessor information, discusses RCA's general-purpose microprocessor—the COSMAC CDP 1802—as well as advanced RCA designs, and describes more than a dozen specific applications. This reprint contains 24 articles, presenting the work of more than 40 RCA engineers.

Electro-optics covers electro-optics work at RCA and has specific sections on light sources, light transmission devices and media, light detectors, electro-optics systems, electro-optics for inspection and detection, and television. This reprint contains 28 articles presenting the work of more than 40 RCA engineers; it also contains several editorial features introducing the major topics.

Automotive electronics presents the technical contributions of more than 30 RCA engineers to research, design, and application of automotive devices, equipment, and systems.

In addition to these three reprints, a limited supply of past reprints is available. All reprints have color covers. A complete list follows:

Reprint	Price	Date
Microprocessor technology (118 pages)	$2.00	1977
Electro-optics (145 pages)	$2.50	1977
Automotive electronics (112 pages)	$2.00	1977
COS/MOS technology (76 pages)	$1.00	1973
Solid state technology (135 pages)	$1.50	1971
Consumer electronics (60 pages)	$1.00	1970
Integrated circuits (88 pages)	$1.00	1967

How to Order . . .

Although single-copy orders will be accepted, minimum orders of five are preferred. Send your name, location, and account number (if a personal order—send check or money order, payable to RCA Technical Communication Programs) to:

Reprints
RCA Technical Communication Programs
Bldg. 204-2
Cherry Hill, N.J. 08101
Phone: PY-4256

Engineering News and Highlights

More Fellows, more PEs

Apparently, one way to elicit reader response is to publish a list of people, and miss some of them. Last issue we published two—a list of RCA engineers who had attained the grade of Fellow of the IEEE and a list of Licensed Professional Engineers at RCA.

Thanks to all of you who wrote in to complete our lists, particularly to Dr. George Brown who called our attention to seven IEEE Fellows left off our original list. We will continue to update our lists as we receive new information. Here are the updates we have thus far:

IEEE Fellows

Name	Awarded
Goldsmith, Alfred N.	1915
VanDyck, Arthur F.	1925
Shackelford, Ben E.	1938
Guy, Raymond F.	1939
Crosby, Murray G.	1943
Seeley, Stuart	1943
Burnap, Robert S.	1947
Ingles, Harry C.	1948
Bingley, F. James	1950
Law, Russell R.	1953
Firestone, William L.	1965
Hittinger, William C.	1967
Cohen, Robert M.	1967
Dodds, Wellesley J.	1972
Pritchard, Dalton H.	1976
Clark, John F.	1976

Licensed professional engineers

Alascom

Henderson, W.	AK-CE4488
Strid, G.	AK-EE4502
Swanson, D.	AK-CE4507

Astro-Electronics

D'Amanda, A.W.	NJ-18747
Schnapf, A.	NJ-9310

Avionics Systems

Aires, R.H.	CA-CS2196

Broadcast Systems

Schacht, W.F.	NJ-12594

Consumer Electronics Division

Chaney, H.E.	IN-15932
Olson, L.A.	IN-12407

Government Communications Systems

Bradshaw, J.L.	NJ-24610

Laboratories

Gange, R.A.	NJ-21860

Missile and Surface Radar

Groman, E.M.	PA-17495E NJ-11557
Ringo, K.A.	OH-E-019719

Picture Tube Division

Ehrlich, M.A.	OH-E040294
Fanale, J.M.	PA-007009E
Ferguson, J.E.	OH-E29169
Follis, G.R.	IN-06773
LeMay, B.B.	OH-E034462
Parker, W.A.	PA-29874-E IN-12907
Pearlman, S.	PA-022917E
Schneider, R.K.	OH-28908
Swander, T.E.	OH-19669
Thall, E.S.	Canadian 5131200 CHEM-MET

Service Company

Williams, J.A., Jr.	VI-325E NH-2464

Solid State Division

Cole, E.W.	M.I.E.R.E.
Davenport, F.A.	M.I.E.R.E.
Free, J.J.	PA-012070E
Gershey, J.T.	PA-23048-E
Medway, N.W.	M.I.E.E.
Stevens, R.	M.I.E.R.E.

Promotions

Astro-Electronics

L. Jones from Senior Engineer to Manager, (Spec) Engineering.

R. Horner from Senior Engineer to Manager, (Spec) Engineering.

Consumer Electronics

Ronald L. Hess from Head, Deflection and Power Supply Systems Research, RCA Laboratories, to Manager, TV Systems Development, New Products Laboratory.

Arthur Kaiman from Member Technical Staff, RCA Laboratories, to Manager, Manufacturing Systems, New Products Laboratory.

Robert M. Rast from Head, TV Systems Technology Research, to Manager, New Products Development, New Products Laboratory.

Recent books by RCA authors

Dynamic Business Strategy
the art of planning for success

Theodore A. Smith
Published by McGraw-Hill
[$12.95]

Author Ted Smith was an Executive Vice President of RCA for 13 years, holding various positions as a general manager of groups of operating units, and serving as Director of Corporate Planning. Subsequently, as a consultant for The Conference Board, he was Associate Director for study of management trends. In this project, leaders in management sciences prepared reports which were published under the title: *Challenge to Leadership: Management in a Changing World.*

The jacket of *Dynamic Business Strategy* offers the following introduction:

"The myth that business strategy must be intuitive costs American industry millions of dollars each year. Reflect on the numerous divestitures, liquidations, and writeoffs that have been taken by otherwise well-managed companies. Strategy is the formula for success . . . and it need not be intuitive."

"Here is a realistic guide that describes step-by-step methods for developing a winning business strategy, for avoiding future pitfalls, and for amplifying current profit potential."

Awards

Eight receive Technical Excellence Awards at Moorestown

William Beckett—for creativity, judgment, and team leadership in design, production and integration of AN/SPY-1A Interface Simulator.

Glenn Everhart—for outstanding development effort on critical computer program modules for the AN/TPQ-27 operation.

George Friedman—for creative and resourceful design effort leading to the development of a Requirements Traceability Program for a complex mass of requirements and functional threads on a classified software development program.

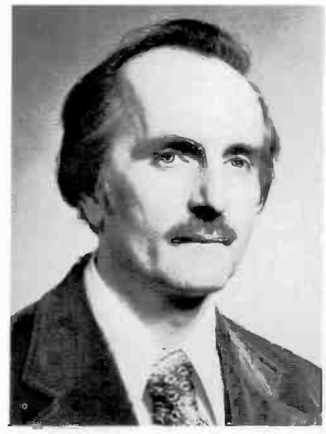
Paul Horton —for personal proficiency and perseverance in developing systems and procedures to assure total operating safety of the AEGIS Combat System during installation, checkout, and system testing at the CSED site.

John Mehling—for special contributions in development of hardware test support software for AN/TPQ-27 equipment subsystems.

Herbert Olson—for technical leadership in the formulation of circuitry and logic for improved integration of the AEGIS Guided Missile Launching System with overall system operation.

David Phillips—for outstanding performance in the definition of AEGIS Command and Decision software performance requirements for advanced AN/SPY-1A ECCM capability.

William Smith—for technical competence and personal initiative demonstrated in the design and implementation of the real-time portion of the AN/SPY-1A Interface Simulator.

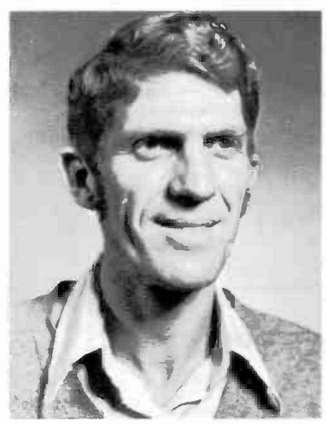


Beckett

Everhart

Friedman

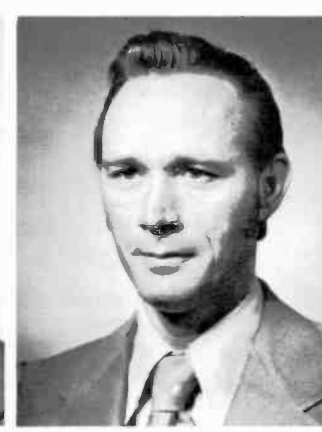
Horton



Mehling

Olson

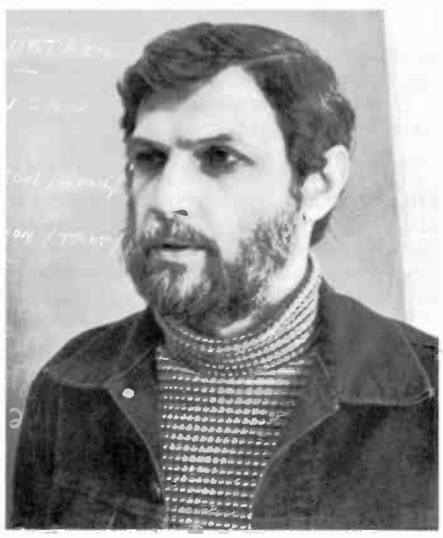
Phillips



Smith

Stiller and Wine are Labs Fellows

Wine



Stiller

Dr. William M. Webster, Vice President, RCA Laboratories, recently appointed **Thomas M. Stiller** and **Charles M. Wine** Fellows of the Technical Staff, in recognition of their outstanding contributions. The designation of Fellow, which was established by RCA Laboratories in 1959, is comparable to the same title used by universities and virtually all technical societies, and is given in recognition of a record of sustained technical contribution in the past and of anticipated continued technical contribution in the future.

Presently the Fellows of the Technical Staff at RCA Laboratories are:

Charles H. Anderson
Kern K.N. Chang
Roger L. Crane
Andrew G.F. Dingwall
Robert E. Flory
James J. Gibson
Joseph J. Hanak
Karl G. Hernqvist
Ralph W. Klopfenstein
Simon Larach
Jacques I. Pankove
Dalton H. Pritchard
Allen H. Simon
Henry S. Sommers, Jr.
Thomas M. Stiller
Chih Chun Wang
Paul K. Weimer
Richard Williams
Charles M. Wine
J. Guy Woodward

Joseph Corso wins annual technical excellence award

All the 1977 technical excellence award winners from Missile and Surface Radar gathered for this photo. **Joe Corso,** the annual award winner is holding his award—flanked by **Max Lehrer** (left), Div. VP and General Manager, MSR, and **Joe Volpe,** Chief Engineer.

Joseph T. Corso, Principal Member, Engineering Staff, at Missile and Surface Radar in Moorestown was recently selected as the winner of the 1977 Annual Technical Excellence Award.

Joseph C. Volpe, Chief Engineer, MSR Engineering Department, in announcing the award said:

"The choice of an annual award winner is never an easy one, and in 1977 CETEC [Chief Engineer's Technical Excellence Committee] selected a record 29 engineers for quarterly Technical Excellence awards. Joe Corso's selection as a winner of the 1977 Annual award, then reflects a level of achievement that is truly extraordinary.

"Although Joe has been with MSR only since 1970, we've had the benefit of his missile guidance expertise for a considerably longer time—from the early 60's when he served as a consultant on missile-related developments leading ultimately to the AEGIS Program. His work has been uniformly superior, as exemplified by... his accomplishments on AEGIS during 1977.

Hap Easter receives two honors

Dr. William L. Firestone (left), Div. VP and General Manager, Avionics Systems, hands **Hap Easter** one of his two awards in a ceremony in Dr. Firestone's office.

Finis C. ("Hap") Easter of RCA Avionics Systems in Van Nuys, California, recently received two honors for his professional and technical activities. He was elected to the College of Fellows of the Institute for the Advancement of Engineering, "in recognition of his outstanding contribution to the advancement of the engineering profession."

His second honor came from the San Fernando Valley Engineers' Council, a group of 22 engineering societies of the various disciplines. "Hap" was one of eight receiving an Engineering Merit Award "for outstanding professional qualities and meritorious achievement within the field of engineering."

Hap, an engineer with RCA for 27 years, has five issued patents, three additional patents pending and several active disclosures. This year he is chairman of the San Fernando Section of IEEE with a membership of some 1700.

Staff Announcements

RCA Records

Paul Potashner, Group Vice President, appointed **Robert D. Summer** President, RCA Records Division.

Consumer Electronics

J.B. Thomas, Manager, Manufacturing Engineering, appointed **Douglas J. McGinnis** Manager, Process Engineering.

President and Chief Executive Officer

Edgar H. Griffiths, President and Chief Executive Officer, announced the following appointments:

Eugene J. Beyer, Jr. is Senior Vice President and General Counsel. In this capacity, he is responsible for the RCA law organization and the Secretary's office.

Steven S. Barone continues as Vice President, Licensing, and reports to the President and Chief Executive Officer.

John V. Regan continues as Vice President, Patent Operations, and reports to **William C. Hittinger,** Executive Vice President, Research and Engineering.

Patent Operations

Harold Christoffersen, Director, Patents, Solid State and Electronic Systems, has appointed **Robert A. Hays,** Resident Patent Counsel, Cherry Hill; and **Birgit E. Morris,** Sr. Managing Patent Attorney.

Edward J. Norton, Director, Patent Planning and Administration, has appointed **Sharon K. Stepno** Manager, Patent Office Washington.

Eugene M. Whitacre, Director, Patents, Consumer Products and Broadcast Equipment, has appointed **Paul J. Rasmussen,** Sr. Managing Patent Attorney; and **Joseph S. Tripoli,** Managing Patent Attorney.

Commercial Communications Systems Division

Adron M. Miller, Manager, RCA Photophone Systems, has appointed **Gordon E. Cordell** as Manager, Product Management, for RCA's line of professional motion picture film records and projectors.

Automated Systems

Fernand F. Martin has been appointed Manager, Radiation Systems Engineering.

Advanced Technology Laboratories

James A. Colligan has been appointed Manager, Marketing for Advanced Technology Laboratories.

RCA Globcom

Eugene F. Murphy, President, RCA Global Communications, Inc., has announced the election of **Dr. Thomas Mathai** to the newly created position of Vice President, Data Services.

RCA Laboratories

Thomas O. Stanley, Staff Vice President Research Programs, has announced that the organization formerly known as Management Information Systems will be restructured as follows: **Marvin Blecker** is appointed Head, Systems Analysis Research; **Emilie M. Lengel** continues as Manager, Automation and Computing Services; and **Warren C. Sayre** is appointed Manager, Administrative Systems.

Solid State Division

Carl R. Turner, Division Vice President Integrated Circuits, and **Gerald B. Herzog,** Staff Vice President, Technology Centers, announced that **Joseph H. Scott,** Director, Integrated Circuit Technology will assume additional responsibilities. He will provide all technical and strategic direction in Silicon and Sapphire Technology within the Solid State Division, RCA Laboratories and Technology Centers. While continuing in his present position under the Staff Vice President, Technology Centers, for this assignment he will report to **Carl R. Turner**, Division Vice President, Integrated Circuits, Solid State Division.

Picture Tube Division

Charles W. Thierfelder, Division Vice President Product Safety, Quality and Reliability, has announced the organization of Product Safety, Quality and Reliability as follows: **Sherman L. Babcock,** Administrator, Technical Quality Programs; **David C. Ballard,** Manager, Product Safety; **Wellesley J. Dodds,** Director, Quality and Reliability Assurance Operations Analysis; **J. Edward Fagan,** Administrator, Quality Assurance Coordination; **Frank J. Hinnekamp,** Manager, Life Test, Reliability and Warranty; and **J. Paul Sasso,** Administrator, Customer Quality Acceptance.

Obituaries

Edward Bliss, an electrical engineer with RCA Global Communications, died April 1, 1978.

Mr. Bliss designed the transmitter for the historic Relay Communications Satellite and for the first Lunar Excursion Module used during the moon landing in 1969. For his accomplishments, he received the RCA Engineering Award in 1970. During his tenure with RCA, he also pioneered the application of computer-aided design techniques to the development of solid-state microwave devices and authored several technical papers on that subject. He was a recognized authority on the design of travelling wave tubes and contributed a chapter on the subject to the *RCA Electron Tube Design* book.

He joined the RCA American Communications Division in 1974 to work on the RCA Satcom Satellite Program. He was part of the launch team that supported two successful launches and conducted the on-order performance checkout.

Nils E. Lindenblad, one of RCA's most prolific inventors, died on February 18. He retired from RCA Laboratories in 1960.

A pioneer in transoceanic radio communications in the 1920's and 1930's, he joined the RCA Corporation in 1920 at the company's transmitting station at Rocky Point, L.I. He transferred to RCA Laboratories in Princeton in 1950.

Mr. Lindenblad was credited with more than 300 patents. He was widely known for his development of the rhombic and slot antennas, the travelling wave tube, and the basic elements of thermoelectric cooling systems. He helped to develop the first wideband television antenna placed on top of New York's Empire State Building in 1938.

A Fellow of the IEEE and the RCA Laboratories, Mr. Lindenblad was awarded the 1958 David Sarnoff Outstanding Achievement Award "for his invention and pioneering development of many important electronic devices and for his research on thermoelectric cooling apparatus."

Barr on IEEE committee

Ken Barr, Component Engineer, at the Consumer Electronics Division in Indianapolis was recently appointed to a three-year term as RCA's representative to serve on the Administrative Committee of the Broadcast, Cable TV and Consumer Electronics Group of the IEEE. Currently, Ken is also the treasurer of the Central Indiana IEEE.

Finite Element Symposium Program Held

An RCA Finite Element Symposium was held on March 13 and 14 at RCA Laboratories in Princeton. About 60 engineers and managers assembled to listen to formal presentations, discuss mutual problems, and, for those with no direct experience, to gain an understanding of this powerful new tool.

Ron Enstrom, RCA Laboratories, was chairman of the program which included speakers from Astro Electronics, Missile and Surface Radar, Solid State Division, Picture Tube Division, and RCA Laboratories as well as a guest speaker from Massachusetts Institute of Technology.

Phillips receives Goldsmith award

John Phillips, Editor of the *RCA Engineer* recently received the 1977 Alfred N. Goldsmith Award of the IEEE Group on Professional Communication.

Established by the Professional Communication Group in 1974, the Alfred N. Goldsmith Award is given in recognition of service within the Group's organization to improve the quality of engineering communication.

Lauffer promoted to Associate Editor, *RCA Engineer*

Bill Lauffer, who has worked as Assistant Editor of the *RCA Engineer* since May 1976, was recently promoted to Associate Editor.

Bill has made important contributions to the quality of the *RCA Engineer* and has contributed to, or initiated, several innovative features.

Willis is new Ed Rep at Consumer Electronics

Don Willis has been appointed Editorial Representative for Consumer Electronics in Indianapolis. Don is a senior engineer and has worked at CE for 15 years on signal circuiting, video tape recorders, and deflection circuits. He has written several articles and holds 17 patents.

As Editorial Representative, Don will assist CE authors with papers for the *RCA Engineer,* and will keep the editors informed of new developments as well as professional activities, awards, publications, and promotions in their areas.

Authors and inventors honored at Moorestown

Fifty-one individuals were honored on February 23 at Missile and Surface Radar's Authors' Reception held in Moorestown, N.J. This reception, hosted by **Joe Volpe,** Chief Engineer, was the eleventh in a series to honor people who have presented or published papers or received patents.

In congratulating the MSR authors and inventors, Mr. Volpe called attention to the efforts involved in professional authorship.

Editorial Representatives

Contact your Editorial Representative, at the extensions listed here, to schedule technical papers and announce your professional activities.

Commercial Communications Systems Division

Broadcast Systems

BILL SEPICH* Camden, N.J. Ext. PC-2156
KRISHNA PRABA Gibbsboro, N.J. Ext. PC-3605
ANDREW BILLIE Meadow Lands, Pa. Ext. 6231

Mobile Communications Systems

FRED BARTON* Meadow Lands, Pa. Ext. 6428

Avionics Systems

STEWART METCHETTE* Van Nuys, Cal. Ext. 3806
JOHN McDONOUGH Van Nuys, Cal. Ext. 3353

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