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Dr. Adam is the author of the book *Microwave Theory and Applications* (Prentice-Hall, 1969). He has three patents in the microwave field, two more pending. He is the author of many articles dealing with microwave measurements and related subjects.

A Half Century of Radar

DAVID K. BARTON, FELLOW, IEEE

I. INTRODUCTION

As THE IEEE celebrates its 100th anniversary, the practitioners of radar look back on fifty years of progress in their specialized field. Although microwave radar has been the dominant concern for most of this period, the earliest efforts and some of the most recent have used other regions of the spectrum—metric and now micrometer wavelengths. The evolutionary development of radar can be traced through this half century, punctuated by several major innovations in techniques and components: the microwave magnetron, high-power klystron and Amplitron transmitting tubes, coherent signal processing, monopulse tracking, pulse compression, electronically steered arrays, digital processing and control, and solid-state microwave devices. By comparing the appearance and performance of typical radar systems developed before and after each of these innovations, we can see how they have affected the art of radar, and we may also be able to predict what future developments will bring to this ever-changing field.

II. THE GATHERING STORM

The title of this section is taken from Winston Churchill's famous history of the 1930's, when the final stages of disarmament from the First World War overlapped the preparations for the Second. Even as the British and French were cutting their military budgets and forces, the future Axis partners were developing modern weapons and organizations to use them. Tactical and strategic air power was an important part of this growing offensive threat. British and U.S. defensive forces, denied the large budgets needed to match their potential enemies, turned to technology in an attempt to bolster their diminished capability. Radar became one of the key elements in this effort, and many military historians give the British Chain Home system equal credit with the Royal Air Force (RAF) fighter pilots in the successful defense of their home islands during the war that came all too soon.

Early radar equipment was adapted from the radio communications field, using HF, VHF, and UHF tubes and antenna techniques. The British, faced with the most urgent need to deploy equipment, designed the Chain Home system to work at 25 MHz. Its antennas were hardly distinguishable from those of short-wave radio stations (Fig. 1). Separate transmitting and receiving antennas were used, the duplexer not having been developed. Much of the rapid progress made by the early British developers can be attributed to Watson-Watt's doctrine of using the third best—the best being unattainable and the second best unavailable until too late [1]. Fortunately, for him and for the RAF his program review groups did not have access to today's procedures and techniques for ensuring optimal solutions to each problem.

In the U.S., time was not quite as pressing, and development of VHF equipment was carried out. By the time of our entry into the war, the 105-MHz SCR-270 (Fig. 2) and the 205-MHz SCR-268 (Fig. 3) were available for use [2]. The success of the SCR-270 in detecting the aircraft approaching Pearl Harbor, and the failure of the associated command and control system, are part of the history of that era. As an example of a phased array radar, the SCR-268 provided a preview of techniques used today.

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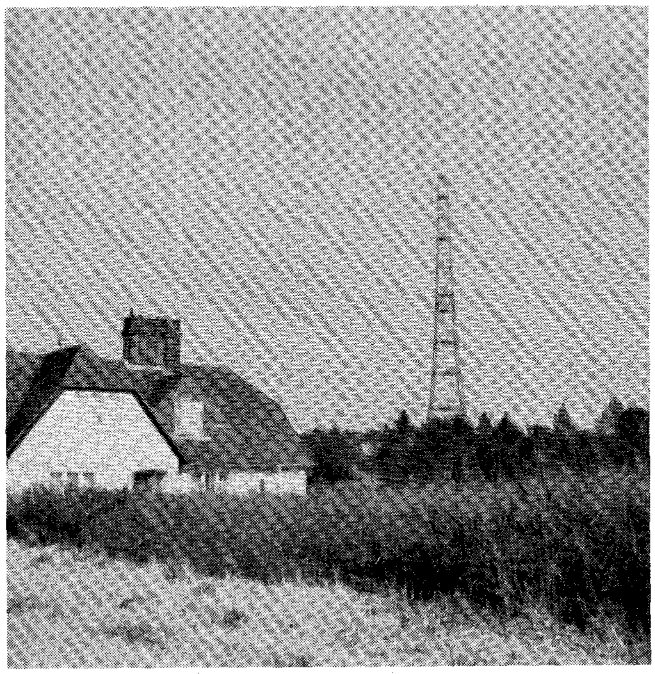

Fig. 1. The only tower remaining from Sir Watson-Watt's radar experiments at Bawdsey, on the North Sea coast of England.

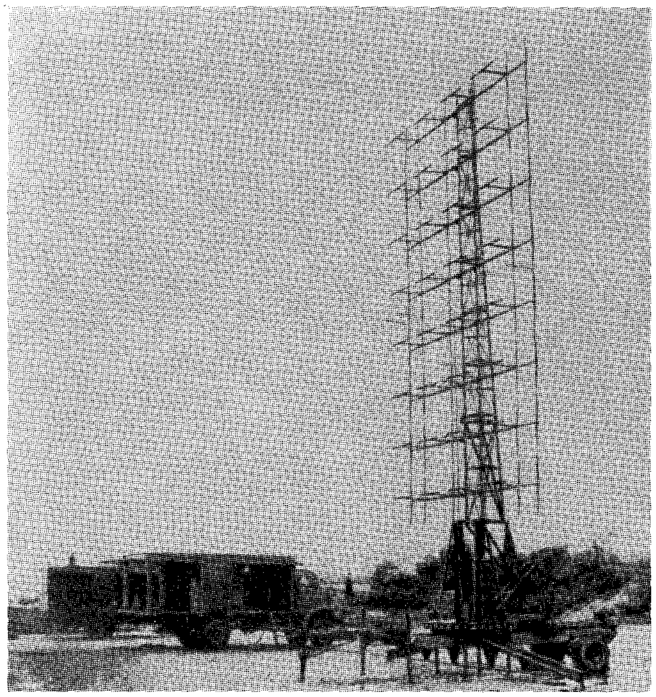

Fig. 2. SCR-270 air surveillance radar.

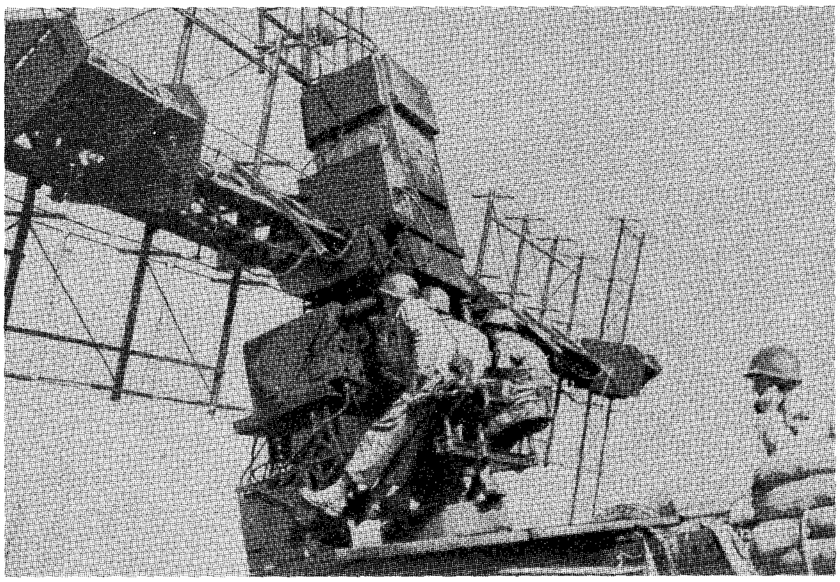

Fig. 3. SCR-268 anti-aircraft tracking radar.

Economy was enhanced by thinning of the array, removing the top and bottom rows from the main (azimuth) antenna, while retaining the entire column of six elements in the elevation array. The array itself was highly redundant, so that damage to a single element would not disable the radar. Processing and tracking, carried out by operators viewing cathode-ray tubes and manually controlling the antenna pedestal, were also redundant. What was lacking was the electronic beam steering used today for search and automatic tracking. Also lacking was the high resolution of modern arrays, which provide milliradian or better accuracy for fire control and missile guidance. The SCR-268 had to rely on accompanying optical trackers to refine its angle data for AA fire control, with the aid of searchlights slaved to the radar beam for night operations.

III. Radar in World War II

Most of the air (and naval) actions in World War II were fought with radar at UHF and below. Early U.S. Navy radar equipment operated at 200 MHz [3]. The XAF and CXAM search radars were designed by the Naval Research Laboratory, and were the first operational radars in our fleet, produced by RCA. These were followed by large-scale production of other 200-MHz systems, the SA, SK, and SR. Other systems at 400, 600, and 1200 MHz became available by the end of the war.

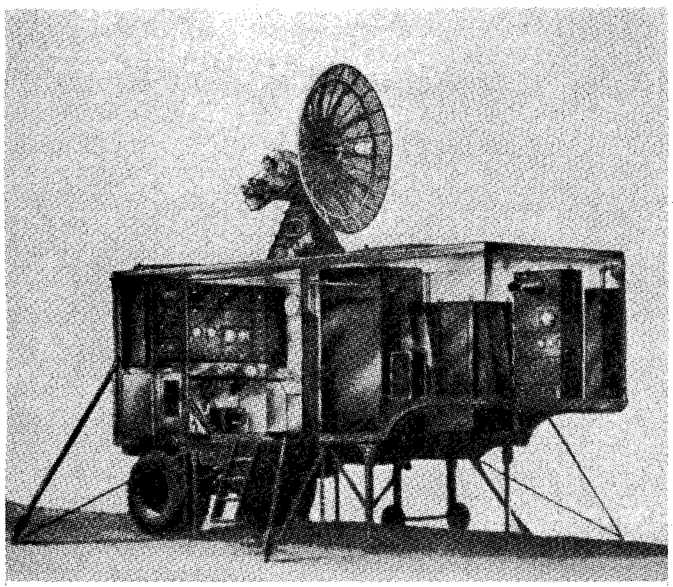

Fig. 4. SCR-584 anti-aircraft gunfire control radar.

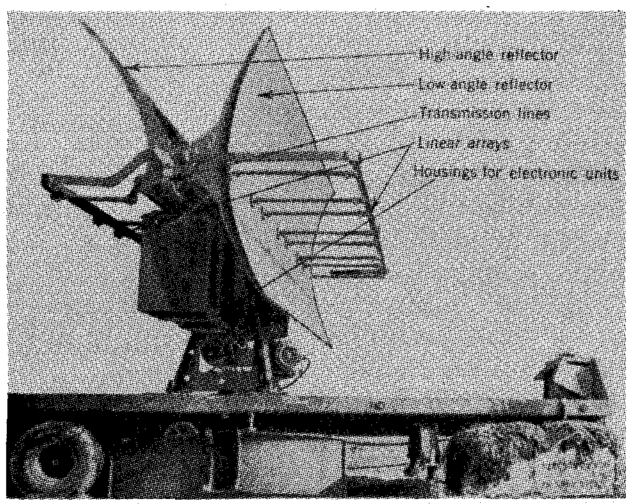

Fig. 5. AN/CPS-1, the first microwave early warning (MEW) radar.

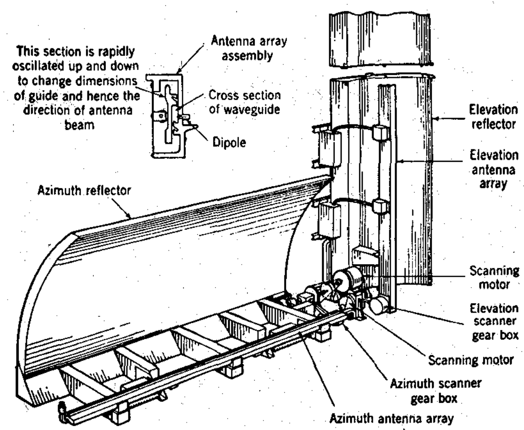

Fig. 6. The Eagle scanner, as used in the AN/MPN-1 precision approach radar.

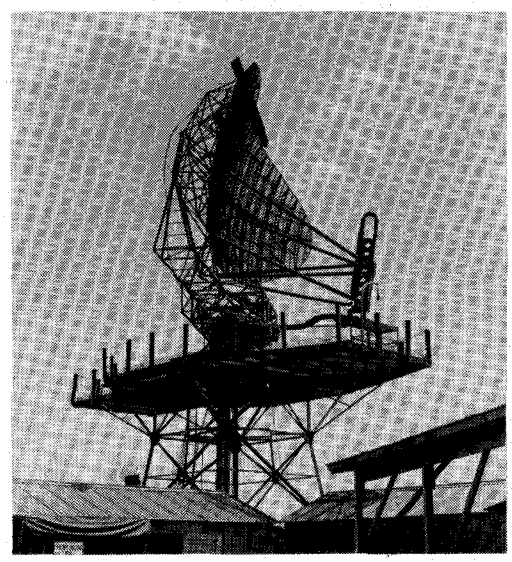

Fig. 7. AN/FPS-20, modernized version of the AN/FPS-3 long-range air surveillance radar, used several feed radiators to obtain cosecant-squared coverage from a parabolic antenna (photo courtesy Bendix Corporation).

Microwave radar made its appearance in 1943, after the magnetron was developed into a high-power, producible device. Low-power klystrons had long been used as local oscillators for superheterodyne receivers, as had parabolic reflector antennas. It required only a year to make the transition from the laboratory magnetron (mid-1940, in England) to the first 10-cm experimental tracker at the MIT Radiation Laboratory. Another year brought the field test model of the XT-1, and by mid-1943 the SCR-584 was being delivered from production [4]. This radar (Fig. 4) had a beamwidth of 4 deg (70 mr), and could track aircraft with an accuracy of about 1.5 mr, adequate for direct input to AA gun directors. Optical tracking continued to supplement the radar data, but the quality of automatic, servo-controlled tracking was such that radar-controlled guns were highly lethal within their design range. With the deployment of shells containing radar proximity fuzes, air defense reached a new high in effectiveness.

Early microwave search radars used parabolic-cylinder antennas (Fig. 5), fed by slotted waveguides. An interesting variant of this design, used for rapid sector-scanning antennas in ground-controlled approach radar, was the Eagle scanner (Fig. 6). It was known that the direction of radiation from a slotted waveguide would change when the transmitting wavelength was varied relative to the waveguide dimensions. Since rapid-tuning magnetrons were not available, the solution was to vary the waveguide dimension, using a mechanical linkage which periodically squeezed the sidewall. This changed the phase velocity within the guide, rephasing the radiation from successive slots to scan the beam through 10 or 20 degrees in angle. Originally developed for airborne radar use, the Eagle scanner was applied to GCA radar [5] in 1944, and it remains in that role today, competing successfully with electronically steered array antennas of much greater capability but higher cost.

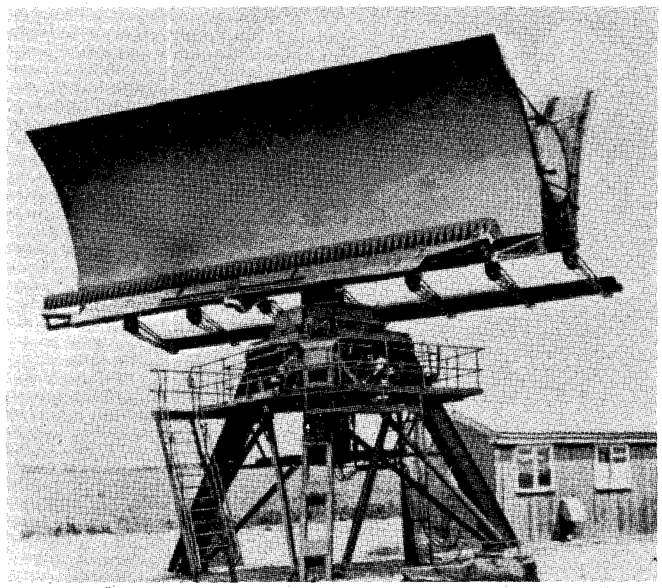

Fig. 8. Modern air defense radar, Type S631, uses back-to-back parabolic cylinders operating at *S*- and *L*-bands to overcome jamming (photo courtesy Marconi Radar Systems).

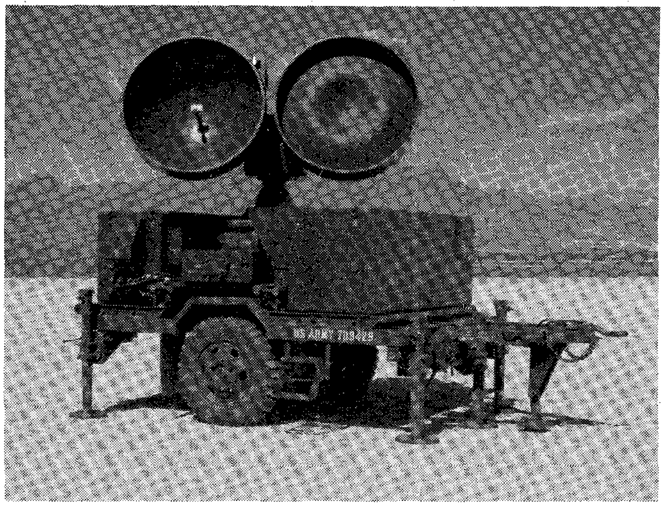

Fig. 9. AN/MPQ-39 CW tracker-illuminator for the Hawk missile system (photo courtesy Raytheon Company).

By the end of the war, most U.S. search radar designs were using the doubly curved parabolic dish, in which shaped elevation coverage could be obtained either with an extended feed, as shown in Fig. 7, or with a single horn feed and a distorted parabolic shape to the reflector. In Europe, the microwave dish antenna was widely used, but it did not completely replace the parabolic cylinder for search radar use. One of the most advanced of today's radars (Fig. 8) seems to have been inspired by the AN/CPS-1, using back-to-back cylindrical reflectors with line feeds. A major innovation, however, is the use of broad-band (equal line length) corporate feeds to achieve very low sidelobes and beam positions which remain invariant with frequency over the entire operating band of the system.

IV. Post-War Radar Developments

Radar moving target indicator (MTI) techniques had been developed at the end of the war [6], too late to have an impact on any of the important air battles. During the late 1940's and 1950's, the area of coherent system operation and Doppler signal processing saw many significant advances. At the beginning of this period, coherent systems (at least in the microwave region) were based primarily on magnetron oscillators, whose random pulse-to-pulse starting phase had to be corrected by locking a "coherent oscillator" in the intermediate frequency stages of the receiver to the transmitted pulse. MTI systems are still designed with this approach to coherence, but the limited accuracy of locking has led to increasing use of the fully coherent, amplifier type of transmitter. High-power Amplitron and klystron tubes, which became available in the 1950's, provides one answer to this need [7], [8]. The travelling-wave-tube RF amplifier is a more recent entry. Using these tubes as final amplifier stages in transmitters which are controlled by very stable master oscillators, great improvements in Doppler rejection of clutter echoes have been achieved. For example, a typical magnetron-oscillator MTI radar may provide 30–40-dB clutter attenuation (although values as high as 50 dB have been obtained). The klystron amplifier system, with proper coherent signal processing, has attained 50–60 dB with equivalent low-PRF (pulse-repetition frequency) waveforms. In medium- and high-PRF modes, such transmitters can support clutter attenuations approaching 90 dB, while CW systems regularly achieve 120 dB. The high-power illuminator of the Hawk surface-to-air missile system (Fig. 9) is an example of this application of klystron transmitters [9].

Another advantage of the amplifier type transmitters is the exploitation of pulse compression. Using either a linear FM sweep (chirp) or some form of discrete phase or frequency coding during the pulse, it is possible to obtain the range resolution of very wide-band signals (approaching a gigahertz, in some cases) while transmitting long pulses of high energy at reasonable peak power levels [10]. Pulse compression has been combined with coherent Doppler signal processing to achieve fine resolution in both range and Doppler. The signal processing techniques used in such systems have included dispersive filters implemented by metallic acoustic delay lines and, more recently, by surface acoustic wave lines. Where extreme clutter attenuation is needed, crystal filters located in the early IF stages of the receiver are still required.

An important post-war development in tracking radar technology was the monopulse tracking system [11]. Although monopulse is sometimes regarded as basically an antenna technique, it involves also the receiver and signal processor. Early work on monopulse systems was done at the Naval Research Laboratory, at General Electric Company, and at the Bell Telephone Laboratory. Most of that work was directed toward military systems, and some remains classified to this day. The first major unclassified development was the RCA instrumentation radar, the

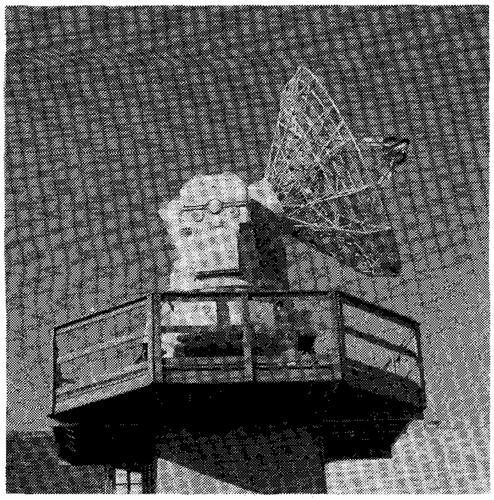

Fig. 10. AN/FPS-16 precision monopulse tracking radar, designed for guided missile range instrumentation and installed around the world during the 1960's (photo courtesy RCA).

AN/FPS-16 (Fig. 10), started in 1954 and delivered from production in 1958. This was the first radar designed to achieve accuracies in the 0.1-mr region (with careful calibration and adjustment), and with its many descendants it forms the foundation of metric instrumentation at most of the western world's guided missile test ranges today [12].

The conventional monopulse antenna consists of a parabolic reflector fed by a multihorn cluster. Where four-horn feeds were originally used, most modern systems use larger feed clusters, often exploiting multimode designs to obtain the necessary control of illumination functions for the on-axis sum beam and the offset difference beams [13]. Important contributions to these designs were made by the Wheeler Laboratories, on behalf of the Bell Telephone Laboratories, and by MIT Lincoln Laboratory. Cassegrainian reflector configurations, some using the polarization-twist technique, have proven quite effective in systems designed to track one target at a time [14]. However, as the number of targets to be tracked has increased, the reflector systems have had to be replaced by phased array radars in many critical military systems and even in some range instrumentation applications.

V. Modern Radar

A. Electronic Scan

Since 1965, the emphasis in U.S. radar developments has been on the phased-array antenna and its supporting subsystems. Indeed, by many in the field, this technology is regarded as the prerequisite for "modern radar." We will discuss briefly some of the issues and trends in electronically scanned radar systems, but will also cover other techniques which should be considered as part of the modern radar era.

The first practical electronically scanned radars were of the frequency scanning variety. An example which remains

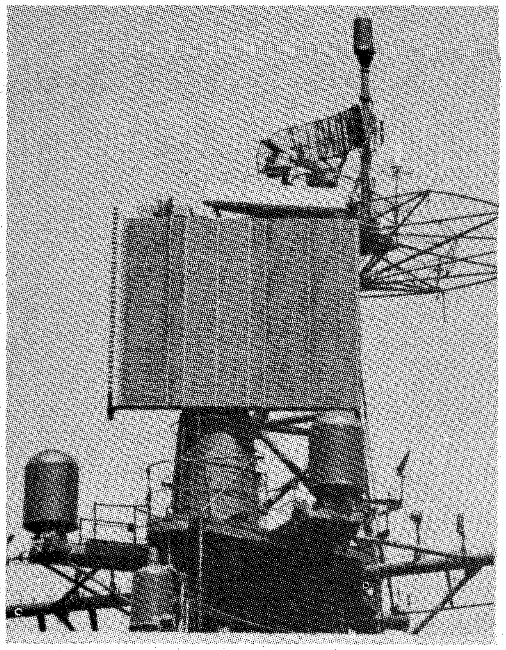

Fig. 11. AN/SPS-48 frequency-scanned 3D radar (photo courtesy ITT Gilfillan).

in extensive use is the AN/SPS-48 frequency scanned 3-ED radar (Fig. 11), in which mechanical rotation in azimuth is combined with electronically programmed elevation scan. Coverage up to about 45 deg in elevation is provided, and deck motion is also corrected by selection of the transmitted RF to place the beams at the desired angle. To overcome the time budget problems that limited the performance of previous 3-D radars of the scanning-beam type, this radar uses a stacked set of beams, into which transmitted pulses are rapidly sequenced, followed by parallel reception in several receiver channels. The serpentine elevation feed structure is visible at the side of the array, which is composed of slotted transmission lines. Ground based versions of this system have also been produced [15].

Phase-scanned arrays, because of their high cost, originally appeared in applications such as space surveillance and anti-ballistic-missile defense. In many cases, the program effort was consumed in the development of a single radar, which never led to further production. The AN/FPS-85 (Fig. 12) is one example [16], and others can be found in the ABM family of the Bell Telephone Laboratories [17]. Radars for instrumentation of U.S. and foreign missile operations have also been built one at a time, examples being the Cobra Dane (Fig. 13) and Cobra Judy radars used by the U.S. to observe Soviet missiles reentering near the Kamchatka peninsula [18]. The first large arrays to be produced in numbers were the Pave Paws radars, installed on the east and west coasts of the U.S. for warning of submarine-launched missile attacks. Two additional units are being added to cover the Gulf Coast and the southern Pacific Coast areas. Each such radar represents a major production task, with thousands of radiating elements and transmit–receive RF modules.

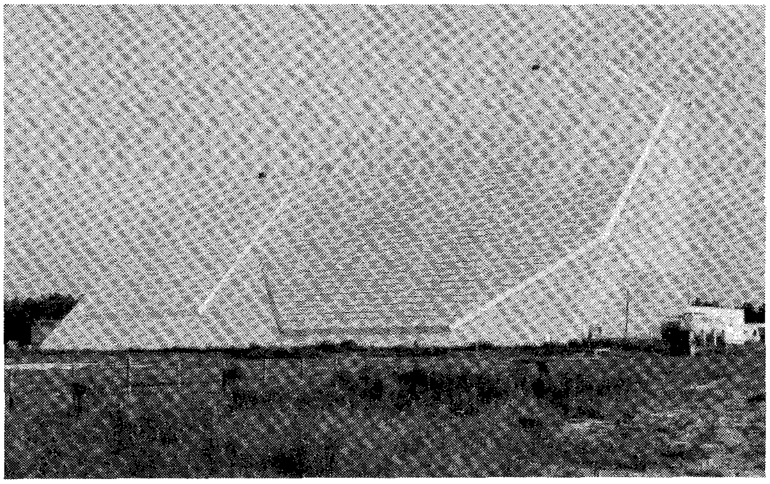

Fig. 12. AN/FPS-85 Spacetrack radar, as completed in 1968 (photo courtesy Bendix Corp.).

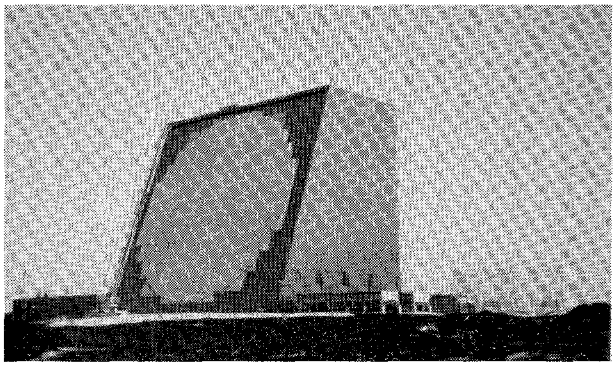

Fig. 13. AN/FPS-108, or Cobra Dane, a large phased-array radar on Shemya Island near the tip of the Aleutians.

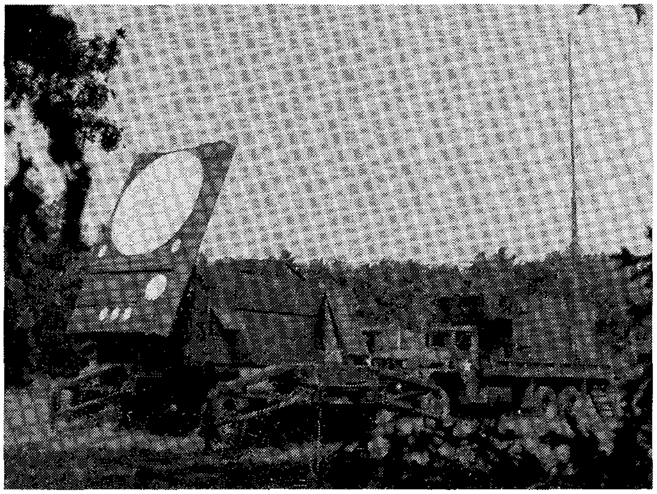

Fig. 14. Multifunction phased array radar for the Patriot missile system (photo courtesy Raytheon Company).

Array radars for tactical use have now gone into production for both Army and Navy systems. The AEGIS multifunction radar, supporting the Navy's anti-air standard missile, uses four array faces, two forward and two aft, on the newest guided missile cruisers. Its array is of the conventional corporate feed type, complicated by the need to provide monopulse sum and difference channels on receive. This is accomplished by dividing the array into receiving subarrays of 64 elements each, so that the triplicate corporate feed networks need only connect the 64 subarray output ports. At the subarray, further division by 64, with individual phase shifters for each element, is performed in circuits common to transmitting and to all monopulse receiving channels [19].

An approach which offers inherently lower cost and greater simplicity is the optically fed array [20], an example of which is the Patriot multifunction radar (Fig. 14). The already refined technology of multimode feed horns, as used in mechanical tracking radars, was applied to illuminate the rear face of the array. The open space between the horns and the array, providing the power division for transmitting and monopulse receiving channels, is the only low-cost phased array component yet developed. Individual phase shifting and radiating elements are controlled by the beam steering computer to direct the beam anywhere within the coverage of the antenna. Designed for coverage of a sector forward of the defense site, the entire radar shelter can be rotated to place this coverage sector where it is most needed, and mutual support of adjacent fire units is relied upon to avoid blind regions. In the case of Patriot, the multifunction radar provides all signals and paths needed to support system operation, from target search and acquisition to terminal homing by the missile.

Other tactical phased arrays in production include the Army's Firefinder radars, AN/TPQ-36 and AN/TPQ-37, which are used to locate and track hostile mortar and artillery shells, and the Air Force AN/TPN-19 ground-controlled approach system for landing aircraft in heavy rain and clouds. All these types have more limited scan sectors than the AEGIS and Patriot arrays, which permits them to use fewer radiating elements. In the case of Firefinder radars, these elements are oversize (larger than the two-thirds wavelength width which is normally needed to control grating lobes in the far field pattern). In the

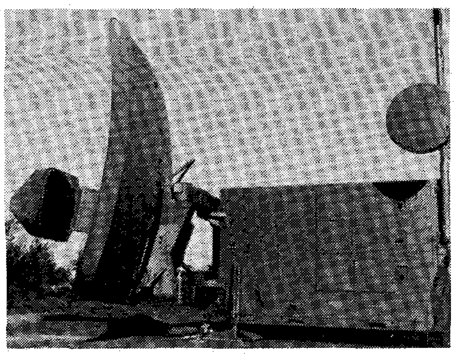

Fig. 15. AN/TPN-25 precision approach radar, part of the AN/TPN-19 landing system, developed for the U.S. Air Force during the 1960's (photo courtesy Raytheon Company).

AN/TPN-19, a different approach is used (Fig. 15). A small (800-element) array is used, more or less in the role of a Cassegrainian subreflector, to illuminate a large reflector surface which is mechanically fixed [21]. The small array is, in turn, illuminated by a monopulse feed which forms sum and difference beams. The several steps in phased-array antenna operation are thus divided and assigned to different portions of the system: the main reflector forms the beam (approximately 1×1 deg, with circular polarization); the small array scans this beam over the 15×20 deg sector coverage about the approach path to the runway; the cluster-horn feed forms the monopulse patterns; finally, a mechanical linkage arrangement permits the entire antenna to be positioned anywhere within 280 deg in azimuth to cover whichever runway is active at a given time. This separation of functions leads to a more economical antenna, appropriate to the needs of GCA systems.

B. Digital Control and Processing

For all these array radar systems, sophisticated control and processing subsystems are needed, to generate and receive different waveforms, to perform Doppler processing of the received signals, to form tracks and schedule beam transmissions for continuing measurement of the targets, and to control the hundreds or thousands of phase shifters that steer the beams. For the most part, these subsystems are implemented digitally, preserving the flexibility necessary to adapt to the diverse functions of the radar.

An example of digital signal processing, which has been applied to the conventional rotating search radar as well as to phased array systems, is the "moving target detector" or MTD [22]. This concept was developed at the MIT Lincoln Laboratories during the 1970's, for use by in the U.S. air traffic control radar systems. It accepts bipolar video signals (in-phase and quadrature) from the phase detectors at the output of the conventional MTI-type receiver, in which signal coherence has been obtained either through use of a coherent transmitter chain or by locking of a COHO to a magnetron pulse. In place of the usual MTI canceller, the MTD uses range gates or sampling strobes, followed by banks of narrow Doppler filters (Fig. 16). In a typical system, there may be 1000 range gates, each feeding 8 or 16 filters, the output of each of which is envelope detected and applied to a detection threshold. Each threshold is in turn controlled by a "range-cell-averaging CFAR," or constant-false-alarm-rate circuit, which evaluates the outputs of several range cells surrounding the one whose threshold is to be controlled, and establishes a threshold level adequate to reject range-extended clutter. Rain or chaff, moving with the wind, will appear in many contiguous range cells and hence will cause the thresholds to rise in whatever Doppler channels correspond to that wind velocity. The system is thus self-adapting to variable clutter velocity. A special zero-velocity channel is used for ground clutter and targets with zero radial velocity (or ambiguous blind velocities). In this channel, the threshold is controlled by a large clutter map, which remembers the magnitude of fixed clutter sources in each range-azimuth cell. Moving targets, not present in the map, can be detected if their amplitudes exceed those of the clutter sources normally present in those same cells. Since the vast majority of cells contain little or no clutter, blind regions are minimized. The MTD thus represents one of the first applications of adaptive filtering and large-scale digital memory to radar signal processing. It makes it possible for conventional scanning search radars to achieve much higher performance than had been available with the MTI systems of the 1960's and 1970's.

Application of MTD-type processing to phased-array radar systems presents the designer with a dilemma: in exploiting the rapid-scan capability of the antenna, the beam should dwell for only a brief period in each position, before shifting rapidly to the next; however, in order to exploit the MTD process the beam must dwell long enough for eight or more pulses to be exchanged with the target. In practice, each beam position should be illuminated by two separate bursts at different repetition rates, to avoid losing targets in blind velocity regions. Thus the scan speed of the array antenna must be compromised in order to exploit the capabilities of the modern signal processor. The scheduling of modern array radars, when looking for targets in cluttered regions of space, must be in multiple-pulse dwells.

Digital processing has also been applied extensively to pulse compression and to generation of waveforms. An interesting example which combines the benefits of digital phase coding with those of linear-FM (chirp) pulse compression has been described [23]. The NRL researchers point out that the "Frank polyphase code" described in the literature of discrete phase coded waveforms is simply the sequence of phase values which would result from sampling a step approximation of linear chirp. By setting the frequency reference at the center of the desired signal band, and by using small steps in both time and frequency, the modified NRL polyphase codes can approach as closely as desired the properties of the chirp waveform: Doppler invariance, symmetrical, low sidelobes, and tolerance of analog circuit bandwidth constraints. At the same time, the waveforms can be generated and processed using digital pipeline circuits which lend themselves to simple and economical implementation.

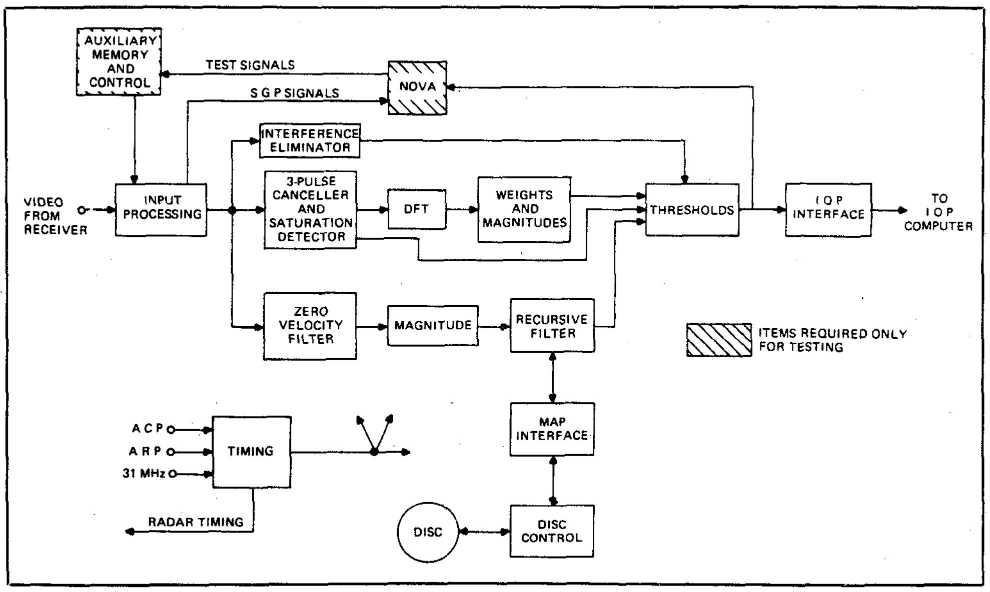

Fig. 16. Block diagram of the moving target detector for airport surveillance radar (courtesy MIT Lincoln Laboratories).

C. Solid-State RF Devices

Solid-state devices have been used in radar from its inception. During the World War II era, these took the form of mixer diodes, the ubiquitous "crystals" whose burnout rendered the radar receiver insensitive. Later, they appeared as transistors in the receiver IF and video circuits, and in digital signal and data processors. In modern radar, they have moved to the RF region, where they serve as low-noise receiving amplifiers and as high-power transmitter sources. For receiving RF amplification, solid-state transistor amplifiers have almost entirely replaced the parametric amplifiers and traveling-wave tubes which were sometimes used to reduce the noise contributions of mixers.

Transmitters based on solid-state sources are still relatively rare in radar. The U.S. Navy has recently sponsored development of a 425-MHz solid-state transmitter for the AN/SPS-40, a long-range 2-D search radar [24]. In this case, the transmitter is a direct replacement for a previous vacuum-tube unit, and its output is combined into a single port which connects to the rotating antenna. Another approach is used in the Pave Paws radar system, where solid-state modules provide transmission and reception from each individual element of the array. In this case, the power goes directly from the final amplifier to the element, where it is combined in space into the radiated plane wave. Phase control for steering precedes the final amplifier, so that source of loss does not effect the output power.

An intermediate class of solid-state transmitters is represented by the AN/TPS-59 (Fig. 17). Here, the power sources are located in each row of the array antenna, and are divided in a corporate structure to feed the individual elements [25]. The elevation beam is formed and scanned by phase shifters which precede the transmitting amplifiers, so phase shifter loss does not appear as a power loss at the output, although corporate structure loss does. As solid-state sources are developed for higher power at higher frequencies, each of these types of solid-state radar transmitter will be used in new applications for microwave search and tracking radars.

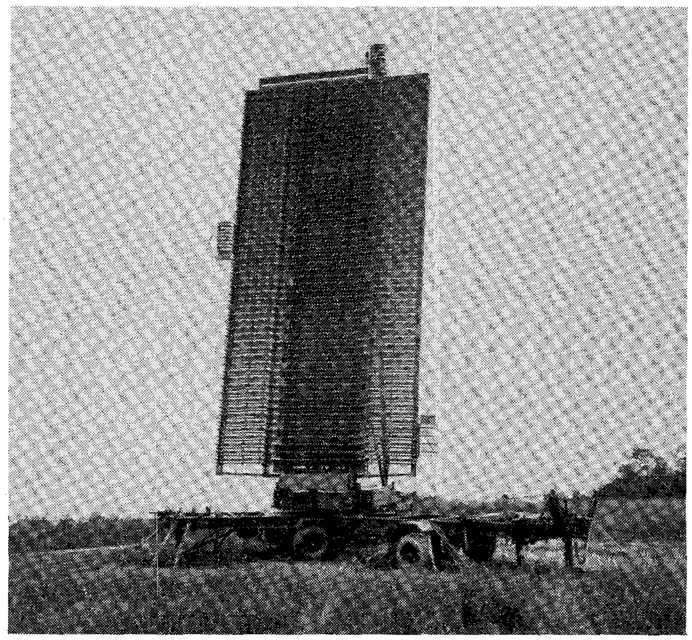

Fig. 17. AN/TPS-59 solid-state *L*-band 3-D radar (photo courtesy General Electric Company).

D. Millimeter Waves

Development of radar in the higher microwave and millimeter-wave bands has proceeded throughout the period from World War II to the present. In each decade, new tubes, components and techniques have appeared to overcome some of the previous limitations [26]. Still, the attenuation of the atmosphere has held back the application

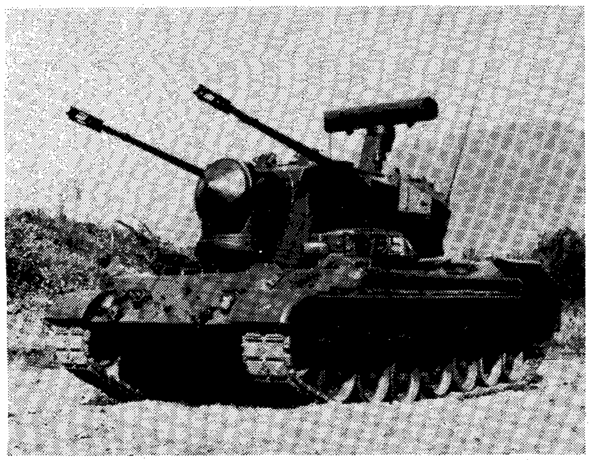

Fig. 18. Flakpanzer AA tank for the Dutch army, showing *X*-band search radar antenna on top and combined *X*- and *Ka*-band tracking antenna at the front of the turret (photo courtesy Hollandse Signaalapparaten).

of millimeter-wave radar for most purposes. Short-range fire control is one area where the upper microwave band has made contributions. Tank-mounted anti-aircraft systems (Fig. 18) can use small tracking antennas and still achieve the narrow beams needed for accurate low-elevation operation. At even shorter ranges, as used in anti-armor missile seekers, millimeter waves can be applied to use the very small antenna diameters which are consistent with this class of munition.

VI. Conclusion

Most of the basic techniques used in modern radar were conceived for use in World War II or soon thereafter, but suffered then from inadequate components and lack of full understanding of theoretical and environmental limitations. Thus the German engineers who attempted to add MTI to the Wurzberg radar, as a counter to Allied chaff, would envy the modern designer who can select from a variety of off-the-shelf stable oscillators and digital storage elements. Today's components make radar design seem easier, and have led to greatly increased demands on modern radar. Unfortunately, these demands tend to outstrip the new capabilities, leading to more complex and expensive radar designs, packed with the newest technology and difficult to get into production and field use.

Modern components and technology make it possible to produce simple, economical equipment meeting most radar requirements. In Europe and elsewhere, many varieties of such radars are in production in increasing quantities. In U.S. commercial radar areas such as sea navigation and aircraft weather avoidance, production of economical equipment is also going forward. The government radar field has not yet fully exploited this potential. The challenge facing the developers of radar today is to find the right compromise between new technology and high performance, on the one hand, and simplicity and economy, on the other. Perhaps a broader perspective into past accomplishments and trends can aid in finding this balance.

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Microwave Communications—An Historical Perspective

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Abstract—**The history of microwave communications includes major discoveries of Morse, Maxwell, Hertz, Marconi, and other pioneers of the radio and electronics fields. This paper traces the early work which led to wireless communications and the long struggle to achieve practical microwave radio. Even though the first microwave line-of-sight systems were demonstrated and placed in service during the 1930's, it was not until the late 1940's and early 1950's that large transcontinental microwave transmission systems were implemented. The 1960's and 1970's witnessed significant progress in the technology and application of line-of-sight microwave communication systems. Other microwave systems including troposcatter, satellite, and millimeter waveguide transmission systems were also developed during the 1960's and 1970's. The past 100 years have witnessed very significant breakthroughs in radio technology, particularly at microwave frequencies, that have had an enormous impact on the world's societies through improved communications for the populace, business, and governments.**

I. Introduction

LONG-DISTANCE communication, both on the earth and over vast regions of space, is one of the major triumphs of microwave technology. The contributions of microwave communication to society have exceeded the greatest hopes of the early pioneers of radio science. Communication has been one of the major drivers in the development and advancement of microwave technology over the past 100 years, and, in fact, led to other applications including radar and radio astronomy.

The history of microwave communication over the past century includes some of the major advances and applications of science and technology. This paper will briefly summarize the early discoveries of the radio and communication arts, the efforts to increase the operating frequency of radio, the first microwave communication links, and the explosive growth of the technology following World War II. Satellite systems, millimeter waveguide communication, and modern microwave radio will also be discussed.

The author apologizes at the outset for omitting discussion on some of the major contributions that have been made in the field, but, in a paper a few pages long, it is only possible to recognize a few of the many major accomplishments that have led to microwave communications as exist today.

It is assumed that most readers are quite familiar with, or have easy access to, literature on the progress in the field during the past 10 to 15 years. The recent advances will be briefly mentioned, but the emphasis of the paper will be on the earlier work that foreshadowed the developments of the 1970's and 1980's.

II. Early History

It is necessary in a study of the history of microwave communications to start with the monumental discoveries and demonstrations in the fields of electrical communication, and the application of the principles of electromagnetic wave propagation to radio.

The first demonstration of electrical communication over a substantial distance was by Samuel F. B. Morse in 1844, with a dot-dash message over a single wire between Baltimore and Washington, DC, using the earth as a return path. Primitive systems and concepts were shown earlier by the Russian, Schilling, and the Germans, Gauss and Weber, but Morse's invention led to the establishment of telegraphy as a viable communication media. The initial installa-

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