JOE FRANK and KENNETH W. O'HAVER

PHASED ARRAY ANTENNA DEVELOPMENT AT THE APPLIED PHYSICS LABORATORY

Complex systems under advanced development for military applications increasingly demand phased array antenna technology. The Fleet Systems Department of the Applied Physics Laboratory has had a major role in developing such technology, including the Advanced Multifunction Array Radar, which served as an early prototype for the Aegis system. To meet the needs of the shipboard Cooperative Engagement Capability, the Laboratory was extensively involved in the creation and implementation of a cylindrical phased array antenna. The more rigorous requirements for airborne Cooperative Engagement Capability terminals spurred the development of active-aperture antennas employing transmit/receive modules based on monolithic microwave integrated circuits. Hybrid architectures are being investigated for active-array radar antennas in an ongoing effort to reduce costs as performance is improved.

INTRODUCTION

The principal motivation for developing phased array antennas has been the need to steer antenna beams rapidly to widely diverse angles. Typically, a phased array radar is used to surveil thousands of angular locations, to track hundreds of targets, and to guide missiles. Such requirements can be met only through repositioning of beams within microseconds. Clearly, electronic beam steering is required because mechanically rotating antennas do not have these capabilities.

For well over thirty years, APL has participated in the development of phased array antennas for Navy radar and communications systems. Early work included contributions to the creation of frequency-scanned arrays and the Typhon system from the late 1950s to the middle 1960s. The Laboratory then developed and demonstrated critical phase-steered array technologies as part of the Advanced Multifunction Array Radar (AMFAR) program and helped to refine phased array antennas for the Aegis system, which incorporated many of the AMFAR technologies. For the Advanced Research Projects Agency (ARPA), the Laboratory developed a variety of patch radiators that are now commonly used in antennas. In the late 1980s, APL led the development of a cylindrical-array antenna for the Navy's Cooperative Engagement Capability (CEC). More recently, APL has had a leading role in devising and perfecting active-aperture antenna technology for Navy communications and radar applications.

EARLY ARRAY ANTENNA DEVELOPMENT

The principle underlying all beam formation is that a wave of energy arrives at an antenna as a planar phase front (Fig. 1). To take advantage of this phenomenon, the antenna must capture the wave's energy by having it add up in phase at some point of collection. Because of its shape, a parabolic dish antenna pointed in the direction
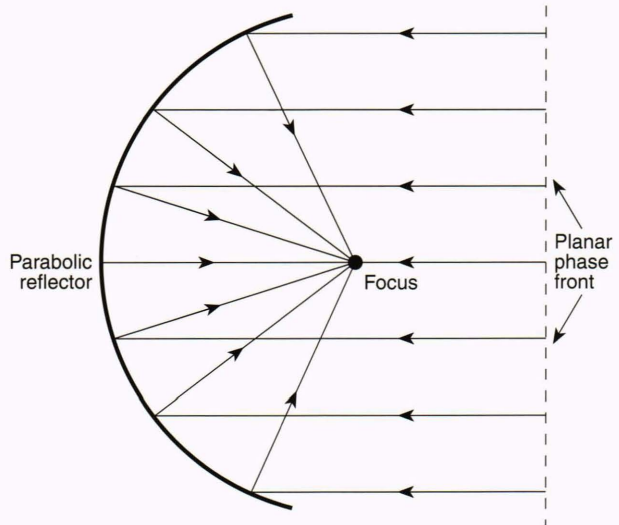

Figure 1. Reflector approach to collecting energy.

of a wave has the property that path lengths from the aperture to the focus of the paraboloid are equal. Since the phases are equal at each point in the planar phase front, the energy from each of the rays will add in phase at the feed. As the dish turns away from the source of energy, the rays will no longer add in phase, and the energy collected in the antenna will be reduced. Parabolic dish antennas were used for many early radar and communications systems and are still common for applications that do not require rapid beam steering.

Early systems for electronic beam steering used frequency scanning techniques[1] in which the beam direction is steered by changing frequency. These systems tap energy periodically along a transmission line and use the periodic locations to radiate energy. Altering frequency

changes the relative phase among elements and steers the beam (Fig. 2A).

The Laboratory helped to develop the SPS-48 and the later low-sidelobe SPS-48E (Fig. 2B) frequency-scanned arrays, which were produced by ITT Gilfillan and have provided the Navy with more than one hundred operational radars on high-value ships. Each system includes an antenna that rotates in azimuth and frequency scans in elevation. These systems, many of which are still in operation, have served the Navy very well for more than thirty years.

Some shortcomings of the frequency scanners are an inability to perform frequency hopping or to operate in the broadband range, since frequency is used for scanning the beam, and a target revisiting time of several seconds because the antenna rotates mechanically.

During the late 1950s, the ability to reposition radar beams within microseconds became a necessity owing to the increasing demands on weapons systems. The Laboratory attempted to meet this need with the Typhon
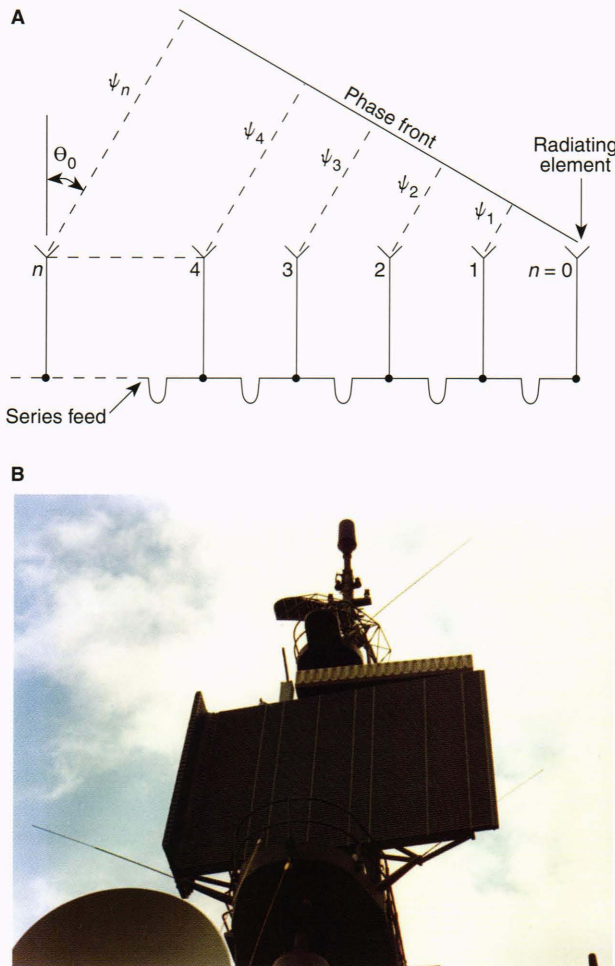
system[2] that switched beams by means of a Luneberg lens (Fig. 3), which has the property that energy entering the lens at a particular point will exit as a plane wave. Energy entering the lens at another point will exit the lens as a plane wave in a different direction. This principle was used to devise a system to switch energy to various input ports using microwave switches, with the resultant beams being switched to different angular locations within a few microseconds. The technical director for this rather complex radar system was APL. Numerous technical problems were solved in the course of developing the system, installing it on the USS *Norton Sound*, and evaluating its ability to detect and track targets. One interesting problem occurred when the Luneberg lens, made of dielectric material, melted after being subjected to high power. The problem was thereafter avoided by using the lens only at low power and then amplifying the energy at each of the output ports with multiple high-power amplifiers (Fig. 3B).

An additional Laboratory effort during the late 1960s and early 1970s led to the development of patch radiators, which were conceived and patented by Rupert H. Collings[3] of the Space Department. Patch radiators are simple thin discs of conducting material that can be mounted onto a structure only a small fraction of a wavelength above a ground plane. The development of phased array antennas using patches as elements was pioneered by Theo C. Cheston and Eugene V. Byron[4] of the Fleet Systems Department. They successfully demonstrated the operation of such arrays experimentally and extended the patch-array concept to include radiating strips, which consist of several contiguous radiating cells united to form a continuous strip antenna. Many types of patch antennas are in common use in modern antennas. The APL effort was carried out for ARPA under project CAMEL.

PHASE-STEERED ARRAY DEVELOPMENT: AMFAR TO AEGIS

When it became apparent that the Typhon system was going to be too complex and expensive for the Navy, the program was canceled in the middle 1960s. In the later stages of the program, researchers at APL and elsewhere
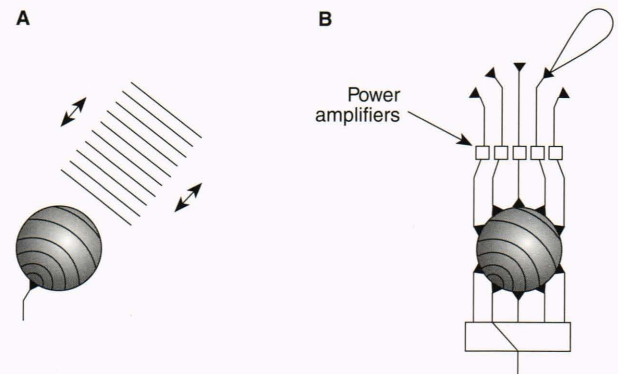
Figure 2. Frequency scanning. **A.** In a frequency-scanned array, the array elements are serially fed, and the beam can be steered to the desired direction (θ_0) by changing the frequency. (ψ = phase change, n = element number.) **B.** The AN/SPS-48E array (produced by ITT Gilfillan) rotates in azimuth and frequency scans in elevation. The sinuous feed used for elevation frequency scanning can be seen at the left side of the antenna.

Figure 3. Typhon radar beam-forming and beam-pointing. **A.** Luneberg dielectric lens focuses an incident plane wave or transmits a plane wave if a signal is injected into a feed. **B.** Transmitting Luneberg lens antenna.

started developing electronic phase shifters, which had not previously been practical, to redirect the beam by changing the phase at each array element and thereby creating a planar phase front in the desired direction (Fig. 4). A phase shifter developed at APL[5] was used as the key element in producing two small (48-element) subarrays. Such projects established the feasibility of phase shifters, power dividers, beam steering, and aperture impedance matching. Given APL's background in these areas, the Navy in 1968 directed the Laboratory to develop an AMFAR. This effort encompassed not only the phased array antenna[6] but also the transmitter, receiver, signal processor, displays, and control. The radar development was completed in 1970 and served as a model for technologies incorporated into the Aegis system (Fig. 5).

During the AMFAR phased array program, led by Cheston, many technical challenges were overcome such as arcing in the phase shifters and the power dividers. Phase-shifter nonlinearities called for a breakthrough in ferrite materials. A new beamformer was also required to provide independent sum and difference monopulse channels for angle estimation. The entire antenna system was nevertheless designed, developed, and tested in one and one-half years, and many of the resulting technologies found their way into the SPY-1A Aegis phased array.

During the AMFAR program, APL developed the concept of an array of subarrays (Fig. 6) in which a subarray (of say sixty-four elements) is fed by a high-power microwave tube during transmission. By using dozens of tubes, very high power levels are achieved, even though the megawatt power levels of conventional high-power radars are not present anywhere in the system. In addition, the large number of tubes provides for redundancy, since the loss of one or two tubes causes very modest degradation. Finally, the tubes can be replaced at sea in a relatively short time. The array of subarrays concept was incorporated by RCA into SPY-1A and carried over into SPY-1B/D.

Once Aegis became a production program, APL continued to contribute to the phased array program. Some notable events were the developments of ANFAST I,
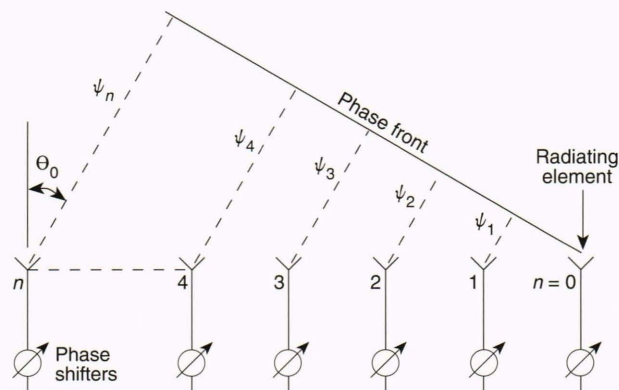
SPY-1B/D, and ANFAST II. The ANFAST I is a near-field antenna measurement facility designed for rapid measurement of the many antenna patterns required of a phased array. The measurement process involves moving a small probe in the near field of an antenna (a few inches from the aperture) and sampling the field at about half-wavelength increments. The near-field pattern can then be processed to obtain the far-field pattern. Since the beam can be steered while the probe is moving, several beams can be measured simultaneously. This technique was conceived by the National Bureau of Standards and the Georgia Institute of Technology and developed by RCA in consultation with APL and others.

The SPY-1B/D antenna represents a significant upgrade to the SPY-1A. The modifications entailed dramatically reducing the antenna sidelobes on reception by changing the basic subarray design, heavily tapering the illumination, and by more carefully controlling amplitude and phase tolerances. A new near-field facility, the ANFAST II, was required to measure the lower sidelobes and to assist in achieving them. This facility is an essential part of the process of fabricating a high-quality, low-sidelobe SPY-1B/D antenna. The ANFAST II was used to measure the phase across the aperture, and the measurements are used to correct phase errors.

Laboratory participation in Aegis has continued with forty ships (one hundred sixty phased arrays) at sea or under construction, and more are planned.

CYLINDRICAL PHASED ARRAYS FOR THE COOPERATIVE ENGAGEMENT CAPABILITY

In the early 1970s, APL began to develop concepts for coordinating the actions of an entire battle group of ships. Those efforts resulted in the Cooperative Engagement Capability (CEC) program in which radar measurement data from battle group radars are shared in near real time to form a composite air picture and to provide cooperative engagements where different units support one another's missile operations. Attaining CEC objectives necessitated a secure communications system with an unprecedented response time, electronic countermeasures resistance, high data rate, and terminal track accuracy to support gridlock alignment. A directive antenna able to point its beam rapidly at any azimuth angle was needed to meet the system-level requirements for data time latency and directive point-to-point network scheduling. These prerequisites ruled out mechanically steered antennas, such as parabolic dishes, and dictated the use of a phased array antenna.

As technical direction agent for the CEC, the Laboratory, working with E-Systems, ECI Division, as the antenna design agent, began developing a prototype phased array antenna in the middle 1980s. Researchers chose a cylindrical array to provide a 360° azimuth scan for a relatively high antenna location on a ship's mast. A major advantage of this approach is that 360° azimuth scan coverage can be obtained without the azimuthal beam broadening and gain loss associated with wide-angle scanning by standard planar phased arrays. Because of the high antenna mounting location, weight was a design determinant and was maintained below 500 lbs.

Figure 4. A phase-steered array in which the phase front is adjusted to steer the beam by individual control of the phase excitation of each element. The beam may be steered to the desired direction (θ_0) by setting the phase shifter at each element to the corresponding phase shift ψ. (n = element number.) The electronic phase shifters provide rapid beam scanning.
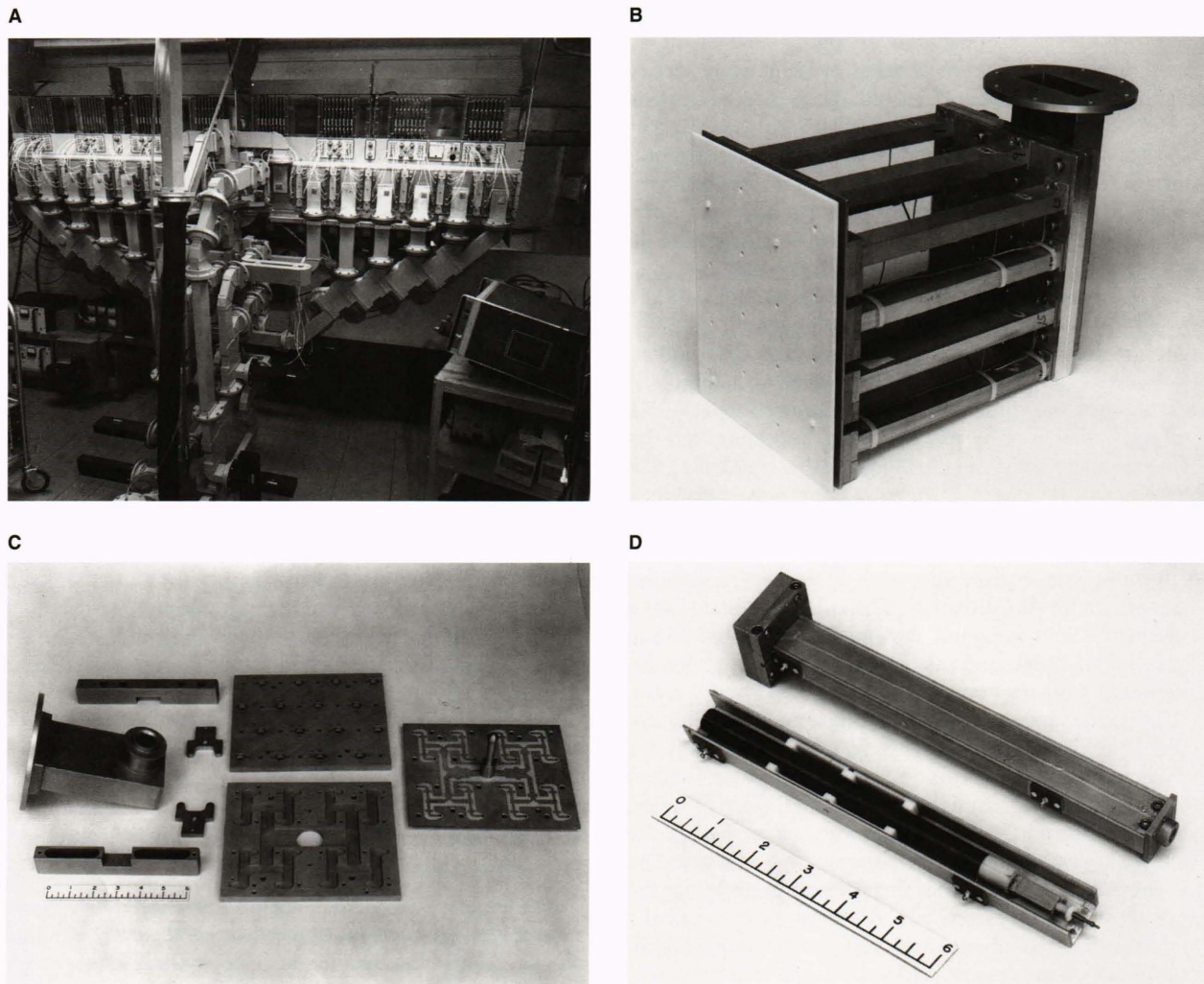
A

B

C

D

Figure 5. Advanced Multifunction Array Radar (AMFAR) phased array. **A.** Completed phased array with beamformer, sixteen subarrays, and phase shifter drivers. **B.** Subarray. **C.** Components of the stripline power divider shown disassembled. **D.** Ferrite phase shifter.

Figure 6. The array of subarrays concept. The schematic shows the components used to support a subarray to feed the combiner, which forms the sum and two difference channels. The diagram shows how twenty-two subarrays would be used to form a radiating aperture. (Σ = sum channel, ΔA = azimuth difference channel, ΔE = elevation difference channel, T/R = transmit/receive.)
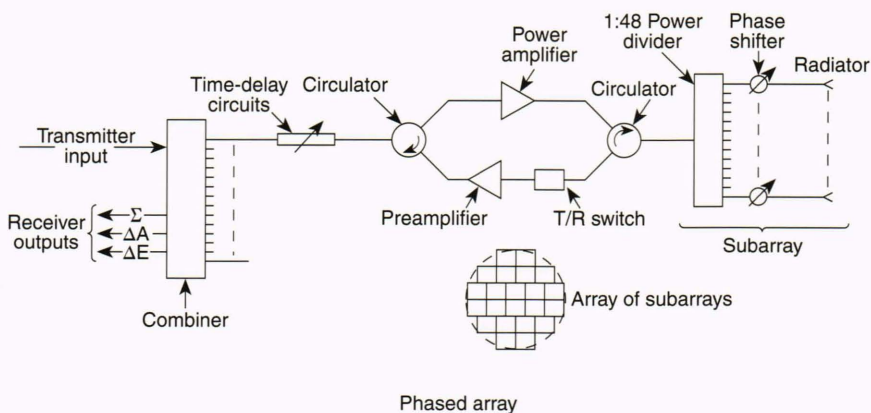
Initial cylindrical-array concepts using ferrite phase shifters and waveguide transmission power dividers, as in the AN/SPY-1 phased arrays, were ruled out owing to excessive weight. The prototype cylindrical-array antenna designed by ECI (Fig. 7) employs microstrip patch elements, PIN-diode (positive-intrinsic-negative) phase shifters, and common transmit/receive microstrip column beamformers. The antenna is divided into several columns of radiating elements spaced evenly around the cylinder. Only one-fourth of the antenna elements are active at any time to create an aperture in the desired azimuth direction, but the aperture is not fixed and can therefore be electronically switched around the cylinder via the double-pole four-throw switches and the amplitude commutator. The phase shifters are used for elevation beam steering, phase compensation of the curved aperture, and fine azimuth beam steering.

The receiving amplitude commutator is a unique feature of the CEC cylindrical array. For electronic countermeasures resistance, the sidelobes of tactical arrays are normally reduced during reception by placing an amplitude taper across the receiving aperture. Amplitude weighting of a cylindrical-array aperture is challenging, since the weighting must move as the aperture moves around the cylinder. An amplitude commutator for cylindrical-array applications was developed at APL in the early l980s.[7] The amplitude commutator used in the CEC cylindrical array derives from the early APL concept.

Cooperative Engagement Capability cylindrical-array antennas were successfully demonstrated at sea aboard operational ships during the CEC demonstration and validation exercise known as Demo 90. After the success of Demo 90, the Navy began a full-scale program to introduce the CEC into the fleet by the mid-1990s. Integration
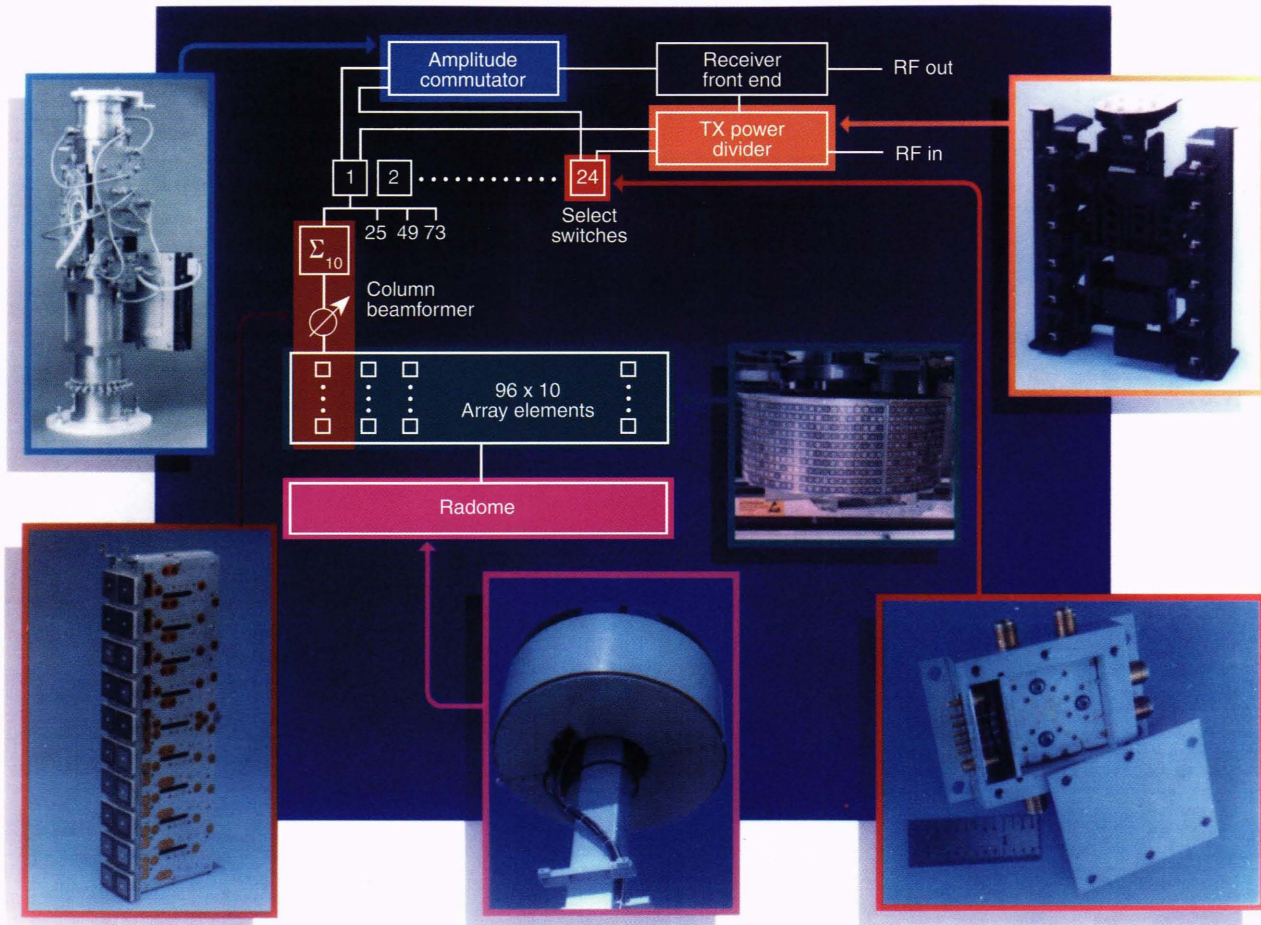

Figure 7. Block diagram of the CEC shipboard cylindrical array, showing microwave assemblies. The cylindrical array contains several columns of radiating elements that are equally spaced around the cylinder. Only one-fourth of the columns are active at any time. The directive beam is steered in azimuth by choosing the active set of contiguous columns via the select switches. The amplitude commutator creates a reception amplitude taper across the active columns for sidelobe reduction. Elevation and fine azimuth beam steering are provided by PIN-diode phase shifters at each element. The column divider/combiner is a microstrip structure common to both transmission and reception signal paths. The transmission (TX) power divider is a waveguide structure to handle the high transmitting power with low loss.

of the system into airborne units (e.g., E-2C) is also planned to realize full CEC operation, including detection of over-the-horizon targets and relaying.

Although airborne CEC terminal functions and requirements are very similar to those for a shipboard CEC, factors such as weight, equipment volume, prime power consumption, cooling needs, and aerodynamic constraints are of particular importance in developing an airborne terminal. Emerging gallium arsenide (GaAs) monolithic microwave integrated circuit (MMIC) technology has made it easier to address such design considerations and has consequently spurred the development of active-aperture antenna technology for airborne CEC antennas.

ACTIVE-APERTURE ANTENNA DEVELOPMENT

The shipboard CEC antenna is an example of a conventional tube-fed passive-array antenna (Fig. 8A) in which RF power is generated at a transmitter below-decks, carried to the antenna via waveguide, divided in the antenna, and directed to the radiating elements by the transmitting beamformer. Phase shifters are used at each element to steer the beam. The power losses between the transmitter and the antenna radiating elements can be high and result in higher required transmitter power and lower system efficiency (increased prime power consumption and cooling). During reception, the phase shifters and receiving beamformer are used to combine received signals in phase before they enter the receiver's front end, which

contains a limiter and low-noise amplifier. On reception, losses in the antenna beamformer before the signals reach the low-noise amplifier are typically also high (particularly for low-sidelobe antennas) and contribute directly to the system noise figure.

The Aegis phase-steered system previously discussed employs an array of subarrays in the transmitting beamformer. Adding dozens of medium-power (tube-based) amplifiers to the transmitting beamformer improved reliability and prevented very high power (megawatts) from appearing at any one location. The next step in the evolutionary process was to place low-power (microwave transistor-based) amplifiers at each element of the phased array. Such arrays are known as active apertures or solid-state phased arrays.

In an active-aperture antenna (Fig. 8B), transmit/receive (T/R) modules are placed at each radiating element of the phased array. The modules typically provide several stages of RF power amplification during transmission, and of low-noise amplification during reception, and feature receiver protection (limiter), a phase shifter for beamsteering during transmission and reception, and an attenuator control for transmission power management and reception gain control. The active-aperture configuration minimizes transmission and reception losses, greatly improves system efficiency during transmission, and reduces system noise during reception. Since over 40 dB of transmission gain typically appears in the T/R module at each element, less RF input power to the anten-
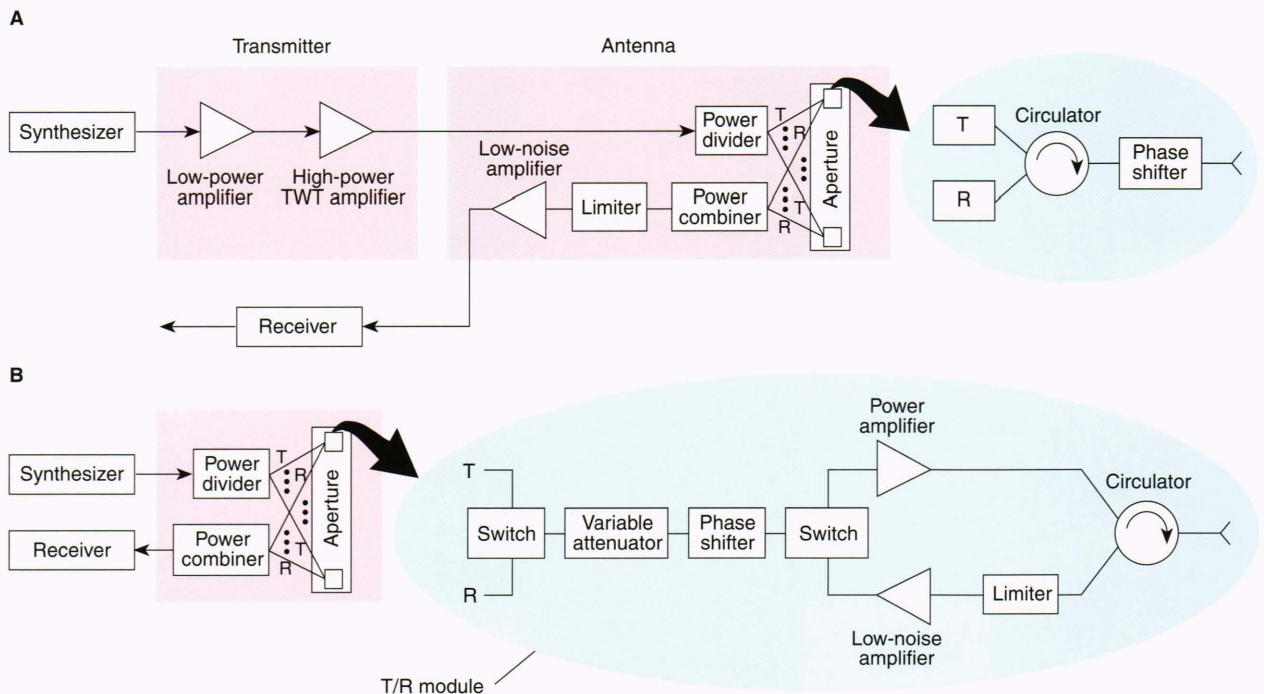

Figure 8. Passive-array and active-aperture antennas. **A.** In the conventional passive system, RF power is generated at the transmitter, carried to the antenna via waveguide, divided in the antenna, and directed to the radiating elements, which contain a phase shifter for beamsteering. The antenna beamformer must handle high power, and the losses between the transmitter and the antenna are typically significant. (TWT = traveling-wave tube.) **B.** In an active-aperture array, transmit/receive (T/R) modules at each element of the array provide amplification for both transmission and reception as well as a phase shifter for beamsteering, which results in low-power beamformers and significantly reduced transmission losses. Since the full transmission gain is accomplished with the T/R module, the conventional transmitter is not needed.

na is required, thus eliminating the need for the conventional high-power transmitter.

The enabling technology for active-aperture antennas is the GaAs MMIC-based T/R module. It permits the required microwave circuit density to be accommodated in the small footprint available, and economical large-quantity production of MMIC's is possible because batch processing is used.

The Laboratory spearheaded the introduction of active-aperture antenna technology into surface-Navy systems. In the late 1980s, the requirements for the airborne CEC made developing active-aperture technology and T/R modules imperative as a way of dramatically decreasing an airborne terminal's weight, prime power consumption, and heat dissipation. Under the technical direction of APL, ITT developed T/R modules providing state-of-the-art power-added efficiency performance (Fig. 9). In late 1991, ECI fabricated an experimental active-aperture array segment containing prototype T/R modules, power supplies, and a liquid-cooling system. After some design iteration, a 560-T/R module pilot build was completed by ITT in early 1993. An active array has been fabricated by ECI and is scheduled to be flight tested in the summer of 1994.

Despite the advantages of active-aperture antennas, such as reduced weight and prime power consumption and increased reliability, real concerns exist about the costs of the T/R modules. Many projections place the cost of modules at $500 to $1000 each when large quantities are used. The CEC in some ways is an ideal application for introducing active-aperture technology because of the relatively small quantity of modules per antenna used. Phased array radars, however, will require several thousand modules per array. For a 5000-element phased array,

consequently, the cost would be $2.5 million to $5 million for the modules per array face, but this cost may be acceptable. With these cost considerations in mind, APL has developed new architectures for employing dramatically fewer modules and still achieving high levels of performance. Subarrays, as used in Aegis, are an alternative when the cost of large numbers of T/R modules becomes prohibitive. Unfortunately, high sidelobes, known as amplitude quantization (AQ) lobes, often appear in the antenna patterns when large subarrays are used. One approach to mitigating AQ lobe effects is to use a hybrid architecture in which the features of active arrays and conventional subarrays are combined.[8]

In the hybrid architecture, elements in the central portion of the aperture are each driven by a T/R module, and, in the outer portion of the aperture, each T/R module drives several elements. Figure 10 shows an example of the hybrid architecture in which each T/R module in the outer ring drives eight elements. Note that phase shifters are required in the outer ring just as they are with a standard array of subarrays. This geometry has the following advantages:

1. In the example given, the number of T/R modules has been reduced to one-third the quantity normally required.

2. About three-fourths of the T/R modules are used in the center of the array and therefore do not suffer phase shifter and power-divider losses. If the phase shifters and power dividers have 2.4 dB of loss, the equivalent array loss is only 0.6 dB.

3. Since the subarrays are in the outer ring, the effect on the receiving sidelobes is reduced because the outer portion of the array illumination is strongly tapered to reduce sidelobes.
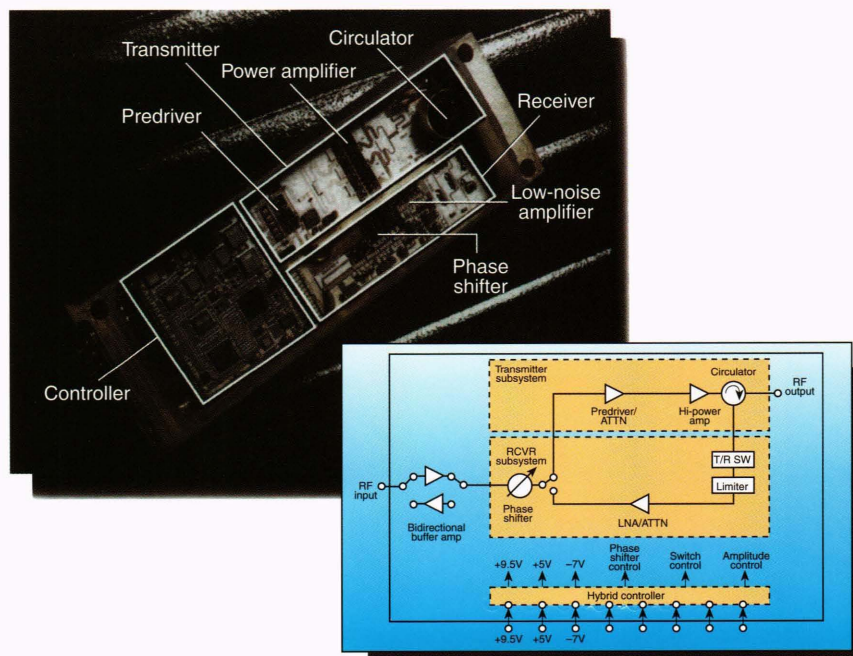

Figure 9. C-band transmit/receive module developed for the CEC. (LNA = low-noise amplifier, ATTN = attenuator, T/R = transmit/receive.)

4. The AQ lobes are at relatively low levels and can be placed in locations where they will do little harm by choosing the subarray spacing very carefully so that AQ lobes rarely reach the horizon where jamming and clutter typically occur.

Figure 11 displays antenna patterns for a hybrid-architecture array in which the subarrays are in the outer ring and have been carefully spaced to minimize AQ lobe effects as noted above. The patterns were generated after several configurations had been tried to achieve optimum results. In Figure 11A, the main beam is in the center of the circle, and the periphery is the location of points 90° from broadside. For this example, the peak sidelobes (Fig. 11B) are 40 dB down from the main beam and are 30° from the horizon (where jamming is most likely). As the antenna scans, a peak sidelobe may reach the horizon, but it will still be more than 40 dB down from the main beam. Peak sidelobes, however, reach the horizon infrequently and may be virtually prevented from doing so by the proper choice of frequency.

The hybrid architecture approach to phased array radars is very general, and many variations are possible.

This technology is consistent with the future growth and commonality of systems for the following reasons:

1. Antenna size may be selected on the basis of the required beamwidth, accuracy, sidelobes, and clutter.

2. The number of modules may be determined by a compromise between required radiated power and cost.

3. As the cost of modules declines, the number of modules may be increased if the military threat increases.

4. Radar requirements can be expected to vary according to ship class. The hybrid architecture approach will enable all ship classes to have the same aperture, and the different radar requirements may then be met simply by varying the number of T/R modules from one ship class to another. This architecture will provide a large degree of commonality among different ship classes.

SUMMARY

The introduction of T/R modules has created a revolution within the radar and communications industries. Dozens of companies and many programs, both in the United States and abroad, are making large investments in MMIC-based T/R modules in the hope of reducing the
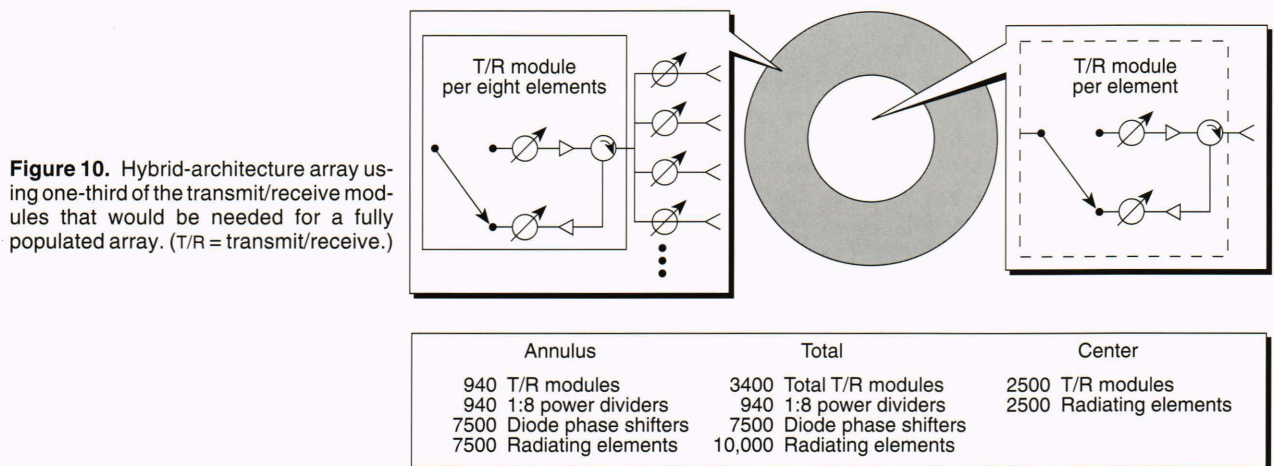

Figure 10. Hybrid-architecture array using one-third of the transmit/receive modules that would be needed for a fully populated array. (T/R = transmit/receive.)
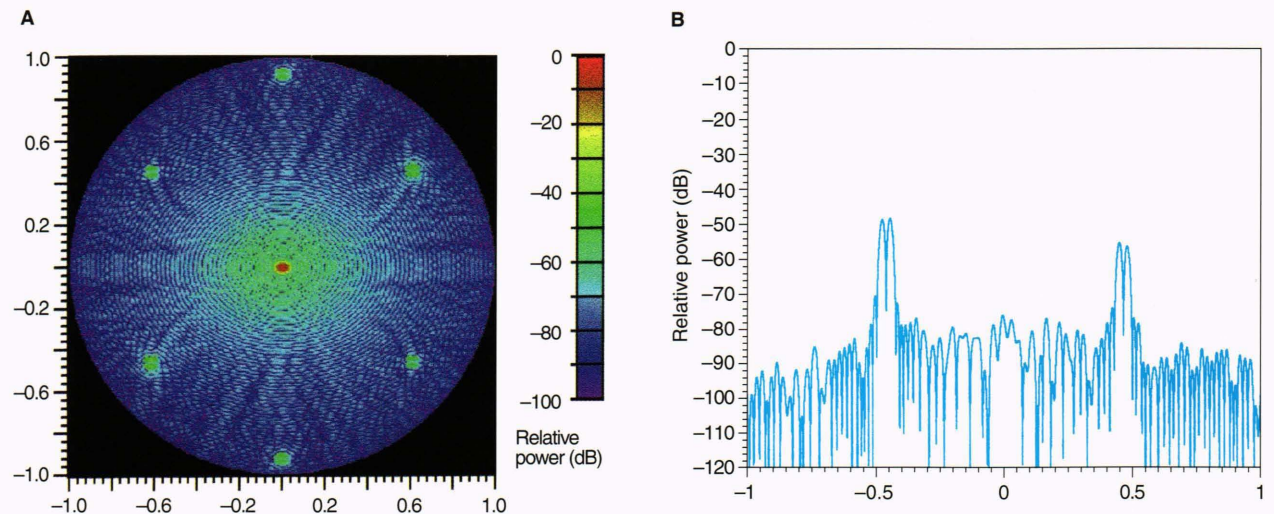
Annulus	Total	Center
940 T/R modules	3400 Total T/R modules	2500 T/R modules
940 1:8 power dividers	940 1:8 power dividers	2500 Radiating elements
7500 Diode phase shifters	7500 Diode phase shifters	
7500 Radiating elements	10,000 Radiating elements	

Figure 11. Receive antenna patterns for a hybrid architecture array with eight-element subarrays. **A.** Sine-space plot showing the main beam at the center and six peak sidelobes. **B.** Elevation cut through a peak sidelobe that is 40 dB below the peak of the beam.

price of systems as capabilities are added. Increased radiated power levels, lower noise levels, reduced power consumption and heat dissipation, and increased bandwidth and reliability are all considered possible. As shown in Table 1, many sponsors expect to achieve these promised advantages. Just as with conventional radars employing tube-based transmitters, years will be expended on the details of design before optimum performance

levels can be realized. The Laboratory is in the vanguard of several radar and communications programs involving the use of active-aperture antenna technology.

The history of technology demonstrates that dramatic new developments can yield improvements measured in orders of magnitude. We look forward to an era in which MMIC-based T/R modules can be used for both military and commercial applications.

Table 1. Phased arrays in production and development.

System	Frequency band	Phase shifter or T/R module	Sponsor	Status
Aegis	S	Ferrite phase shifter	U.S. Navy	Production
Patriot	C	Ferrite phase shifter	U.S. Army	Production
B-1	X	Ferrite phase shifter	U.S. Air Force	Production
TPQ-37	S	Diode phase shifter	U.S. Army	Production
TPS-59	L	T/R Module	U.S. Marine Corps	Production
AWACS	S	Ferrite phase shifter	U.S. Air Force	Production
COBRA	C	T/R Module	Europe	Development
FSX	X	T/R Module	Japan	Development
GBR	X	T/R Module	U.S. Army	Development
CEC	C	T/R Module	U.S. Navy	Development
ATDRSS	S	T/R Module	NASA	Development

Note: AWACS = Airborne Warning and Control System, COBRA = counter-battery radar, GBR = ground-based radar, CEC = Cooperative Engagement Capability, ATDRSS = Advanced Tactical Data Relay Satellite System, T/R = transmit/receive.

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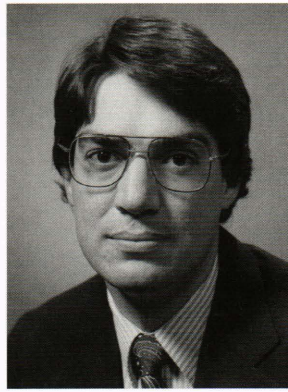
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