Role of Radar in Microwaves

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Invited Paper

***Abstract*—Radar has been highly influenced by the technology of microwaves, and likewise the development of microwaves has been significantly affected by the needs of radar. This paper addresses the relation between the two. It begins by briefly describing the introduction of microwave radar in World War II that was a major factor in the Allies achieving success in air defense and antisubmarine warfare. Microwave radar developments during and after the war are reviewed, along with a listing of current military and civilian applications. The dependence of modern radar on digital processing (with clock rates at microwave frequencies), high-power transmitters, and sophisticated antennas is discussed. The paper concludes by mentioning possible future directions for radar, and briefly describes two examples of future radar system opportunities. These are the ubiquitous radar (one that looks everywhere all the time so as to allow simultaneous rather than sequential performance of multiple functions), and high-power transportable millimeter-wave radar based on the gyroklystron amplifier. The message of this paper is that microwaves and radar have mutually benefited from one another and that radar still offers many opportunities for microwave engineers to demonstrate their ingenuity and creativity.**

***Index Terms*—History, radar.**

I. Beginnings of Microwave Radar

SIGNIFICANT advances in engineering often require both the *push* of technology and the *pull* of an application that offers some economic, societal, or military benefit. The rapid advance in microwaves in the early 1940s was due to the needs (the pull) of military air-defense radar. Microwave technology (the push), however, began approximately 50 years earlier, in the late 1880s, with the classical experiments of the German scientist Heinrich Hertz. He demonstrated experimentally the theoretical predictions of J. C. Maxwell that both radio waves and optical waves were electromagnetic phenomena obeying the same fundamental laws [1]. Hertz, who might be called the first radar scientist, employed what would now be called a radar, albeit crude, to demonstrate the reflection of radio waves from objects. His radar-like apparatus had a spark-gap generator that excited a dipole that fed a parabolic cylinder antenna. The radiated energy was at a microwave frequency in the vicinity of 450 MHz. A little later, in the mid-1890s, J. C. Bose in Calcutta, India, repeated the experiments of Hertz with an improved apparatus, but at much higher frequencies, ranging from 60 to 120 GHz (millimeter waves) [2], [3]. Bose also demonstrated guided-wave propagation in a rectangular metal tube (or waveguide), as well as dielectric lenses and flared waveguide horns used as antennas. Theoretical analysis by Lord Rayleigh [4] of electromagnetic propagation in circular and rectangular waveguides appeared in publication in 1897 on his return from visiting Bose in his Calcutta laboratory.

By 1900, there had been a good start to the exploration of microwaves, both experimentally and theoretically, but nothing much further seems to have happened until the 1930s. The microwave technology of 1900 lacked a transmitter with adequate power, a sensitive receiver, and an application that required operation at microwaves. By the late 1930s, however, the superheterodyne receiver was becoming available at the higher frequencies, as was the semiconductor diode mixer. The application that drove the rapid development of microwaves, beginning about 1940, was military air defense.

In the middle 1930s, the basic concept of radar had been independently and almost simultaneously discovered by eight of the major countries of the world with experience in radio technology [5]. These early radars were all at VHF (100 and 200 MHz being typical for U.S. Navy and Army systems). VHF represented the frontier of electronics technology at that time. (The British Chain Home radars, which were given credit for thwarting the attack of German bombers in 1940, operated at the even lower frequencies of 25–30 MHz.) Most of the countries that developed VHF radars by the start of World War II in September 1939 realized that much higher frequencies were needed so that narrow beamwidths could be obtained with smaller size antennas. Smaller antennas allowed radars to be mobile and easier to place on aircraft. A typical frequency goal was 3 GHz (10-cm wavelength). The chief limitation in 1940, however, to attaining a useful microwave radar was the lack of a high-power transmitter.

There were a number of attempts to develop microwave radar in the late 1930s using the split-anode version of the magnetron that employed an external tuned circuit. This type of magnetron was quite limited in power. At a frequency of about 3 GHz (S-band), the split-anode magnetron generated in the vicinity of 10-W continuous wave (CW), much too small for military air-defense radar application. The major breakthrough in microwave high-power generation came with the invention of the cavity magnetron by the British in 1940. This RF power source made microwave radar a reality. Its practical realization was due, in large part, to the earlier pioneering work on microwave cavity resonators performed at Stanford University, Stanford, CA.

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In the late 1930s, W. W. Hansen, a physicist at Stanford University, explored the properties of microwave cavity resonators for the purpose of accelerating an electron beam. His interest was not in radar, but in providing experimental particle physicists with a linear accelerator ("atom smasher"). The understanding of microwave cavity resonators resulting from the work of W. W. Hansen led two of his colleagues at Stanford University, Russell and Sigurd Varian, to apply his research to the development of the first klystron amplifier, which was described in a paper published in 1939 [6]. The Varian brothers were interested in demonstrating a radar for the detection of aircraft [7]. In spite of its potential, the klystron high-power microwave transmitter was only of minor interest during World War II and was not used in any radars or developed much further. It was overshadowed by the excitement offered by the magnetron. The inventors of the British magnetron acknowledged, however, that the 1939 publication of the klystron paper by the Varian brothers led them to apply the resonant cavity to the magnetron [8], which was the key to the magnetron's success as a high-power source of microwave energy. Today, the klystron is an important high-power device used in many radar applications where high power and stable signals are needed, whereas the magnetron is now used only in radars where high power or good doppler processing is not required.

II. Microwave Radar in World War II

The British were fully occupied in 1940 and 1941 in acquiring the means needed to fight the Germans. In the fall of 1940, the British shared the secret of the cavity magnetron with the U.S. even though the U.S. had not yet entered the war and still claimed to be a neutral. At that time, however, the U.S. was building up its military strength and had just begun to organize the Massachusetts Institute of Technology (MIT) Radiation Laboratory to pursue the use of radar for military purposes [9]. A major goal of the MIT Radiation Laboratory was to apply the technology of the British cavity magnetron to the development of microwave radar. This was a remarkably successful undertaking. Scientists, engineers, and supporting personnel had to be recruited to work on something that never before existed. They rapidly provided the basic advances in technology and systems that allowed industry to manufacture microwave radars in quantity to be placed in the hands of the military in time to have a significant effect on the course of World War II. At its peak, there were almost 4000 personnel at the MIT Radiation Laboratory. None were radar experts when they arrived, but they quickly acquired the expertise needed to develop over 100 different radar equipments in the almost five years of the laboratory's existence. (In peace time, it is hard to obtain a new operational radar system in less than 15 years.) Most professional employees were in their 20s or early 30s, and the few in their 40s were considered to be "senior citizens." The MIT Radiation Laboratory is a good example of what can be accomplished when talented motivated people are recruited and given the facilities and freedom to achieve what is needed. In addition to the MIT Radiation Laboratory, important microwave radar developments were pursued by the Bell Telephone Laboratories and the British. Microwaves gave the Allies (U.S. and U.K.) a decided advantage over the Axis powers (Germany, Italy, and Japan), who were far behind in the application of microwave technology and could not catch up in time.

VHF radar, which was the type of radar available during the early years of Wold War II, is given credit for the following:

- stopping the German Air Force from winning the Battle of Britain (the large air raids on civilian populations in London and other British cities during the fall of 1940 and winter of 1941);
- the British defeat of the Italian Navy in the night battle off the Cape of Matapan in March 1940, when the Italian ships never saw the British ships since they had no radar, but the British did;
- the U.S. Navy's defeat of the Japanese aircraft carriers in their attack on Midway Island in March 1942, which was considered the turning point in naval warfare in the Pacific;
- other successful air-defense engagements by the U.S. Navy in the western Pacific against the Japanese.

The introduction of microwave radar in early 1943 by the Allies was a major surprise to the German military. They were not aware that it was practical to build radars at these frequencies. The serious threat of German submarines to Allied ships traveling in the Atlantic Ocean with vital supplies for the besieged British was finally defeated in the Spring of 1943 when Allied aircraft equipped with S-band air-to-surface surveillance radar caught the German submarines while they were on the surface. (In World War II, submarines had to be on the surface to move quickly from one point to another or to recharge batteries, usually at night.) German submarines had no countermeasures or intercept receivers at microwave frequencies. Admiral Doenitz, the Commander of the German submarine forces, is quoted as saying [10] the following: "The enemy deprived the U-boat of its essential nature—namely the element of surprise—by means of radar. With these methods . . . he had conquered the U-boat menace. The scientists who have created radar have been called the saviors of their country." The radars he was talking about were the British airborne microwave radar known as the ASV Mark III and the U.S. microwave radar known as the SCR-517. The British ASV Mark III was derived from the H2S, an S-band air-to-surface radar developed as a means for night bombers to target German cities. The Germans captured a British bomber downed near Rotterdam carrying the H2S in February 1943, but the German military did not realize that knowledge of the H2S would be important for the submarine navy to know and did not reveal it to them until it was too late. According to Louis Brown [11]:

> "A fierce secrecy restricted knowledge of Allied microwave capability within the Kriegsmarine. Nothing was withheld from the top command levels, but they lacked the electronic knowledge and experience that would have allowed them to evaluate the rapidly changing stream of information from which they had to make decisions. Those who did have the knowledge and experience lacked an easy channel of communications with those at the top and were unable to help them sort out fact from fiction."

When the U.S. introduced the very capable microwave (S-band) SCR-584 antiaircraft fire-control radar during the amphibious landing at Anzio in Italy in March 1944, it caught the Germans defending Anzio by surprise since their electronic warfare measures were prepared only for combating VHF radars. In the Pacific Ocean, the SJ microwave (S-band) radar introduced in August 1942 is credited with giving U.S. submarines a decided advantage in their ability to find and destroy Japanese ships in the western Pacific [12].

There were many factors that allowed the Allies to defeat the Axis forces in Wold War II, but the introduction of radar was one of the most important. There is no way to know whether the Allies would have lost the war if they did not have radar, but it is quite clear that there would have been more losses and a longer time needed to win the war if there were no radar.

It might be noted that the development of the cavity magnetron early during World War II was not limited to the British. Japan invented the microwave magnetron before the British and, in some cases, had more advanced designs [13]. The Japanese, however, did not exploit this advantage. Their research and development (R&D) was under the strict control of the military, who regarded such technology as not directly applicable to practical weapons and ordered further development stopped [14]. On the other hand, in the U.S. and Great Britain, military R&D was under the control of civilians who appreciated the potential of new technologies and had the freedom to turn them into capabilities that were quickly put in the hands of those who needed them. The Soviet Union also invented a microwave cavity magnetron, as early as 1937. It was described in a paper that appeared in the U.S. in the PROCEEDINGS OF THE IRE in 1944, at the height of the war [15]. The Soviet Union could not exploit its development because of the disruption caused by the German invasion of the Soviet Union in June 1941. The fact that it was disclosed in the open literature during the middle of the war indicates the state of chaos that must have existed in radar in the Soviet Union at that time. As mentioned, Japan also invented the microwave cavity magnetron, but they did not share their knowledge with their ally Germany.

One might conclude from the above and other similar examples that military radar development in the hands of civilians in the democratic countries (U.S. and U.K.) was much more successful than when military radar development was tightly controlled by the military in totalitarian countries (Japan, Russia, Germany, and Italy).

In addition to the magnetron as the first high-power microwave radar transmitter, the successful development of microwave radar in World War II required advances in the theory and practice of propagation in waveguides, the development of microwave circuit devices that were needed to replace the lumped-circuit components of the lower frequencies, the development of directive antennas suitable for microwave radar, understanding of propagation within the Earth's atmosphere, and knowledge of the scattering from targets and the environment (clutter). Much of this work was performed at the MIT Radiation Laboratory. It was well documented in 28 volumes published by McGraw-Hill and is now available on CD ROM [16]. More than 50 years after their publication, the several volumes of the "Radiation Laboratory Series" on microwaves and antennas still are important sources of information for the microwave engineer.

III. POST-WAR MICROWAVE DEVELOPMENT

At the end of World War II, pressure to rapidly advance the art of radar and other military systems was considerably reduced. Most of those involved in military radar turned to other pursuits in science and technology. The pace of development slowed and the chief efforts were in completing what had been started during the war. The immediate post-war developments included the introduction of the first long-range microwave (S-band) air-surveillance radar with doppler processing [or moving target indication (MTI)] and the high-power klystron amplifier. The latter is especially interesting because of the manner in which it was introduced to radar and the benefits it provided.

It was mentioned that the klystron power amplifier was invented before the magnetron oscillator, but it was the magnetron that was used exclusively in World War II microwave radar. After the war, the physicists at Stanford University returned to what they were doing prior to the war, which was developing linear accelerators for studying high-energy particle physics. The klystron evolved at Stanford University from its use in the linear accelerator. Stanford University extended its pre-war work and, in 1953, a paper was published in the PROCEEDINGS OF THE IRE describing a high-power S-band klystron that produced 20 MW of peak power and 2.4-kW average power [17]. (Later klystrons developed by others were capable of about 1-MW average power.) Not only is the average power of a klystron much greater than that of the magnetron, the klystron can generate a highly stable signal so that considerably better radars can be obtained for detecting moving targets in the midst of heavy clutter echoes (using doppler processing). The klystron is a power amplifier, which means that its signal waveforms can be quite sophisticated, as is needed for pulse compression and other applications. Today, the klystron or some variant of linear-beam tube [the Twystron, clustered-cavity klystron, and traveling-wave tube (TWT)] is often the first choice for a high-power source of microwave energy for high-performance radars.

Radar development is given credit for having a significant effect on the spawning of several other fields of technology and science. These include microwave communications, microwave spectroscopy, radio and radar astronomy, the maser, holography, nuclear magnetic resonance, air-traffic control, and the first system application of digital computers (the SAGE air-defense system). In addition, it can be said that the success of radar is the reason for so much activity in electronic warfare, stealth, and antiradiation missiles, all of which are designed to reduce the effectiveness of military radar. These three areas probably receive more funding than does radar.

IV. MICROWAVE RADAR APPLICATIONS

The first practical implementation of radar was for military purposes. This is still its major application. Throughout the years, most of the advances in radar technology and capabilities, whether for civilian or military needs, were driven mainly by the needs of the military and were funded by the military. This is still true today so that the capabilities of most civilian radar applications can be traced to some prior military radar development.

Military Applications of Radar:

Air defense (surface based)
- Air surveillance at long, medium, and short ranges.
- Battle management, weapon control.
- Missile guidance and fuzing.

Air defense (airborne)
- Airborne air-surveillance (AWACS and E2C).
- Air-to-air combat.

Ballistic missile defense
- Early warning.
- Intercontinental ballistic missile defense.
- Tactical ballistic missile defense.

Space surveillance and antisatellite

Land warfare
- Battlefield surveillance of fixed and moving targets.
- Mortar and artillery detection and location.
- Mine detection.
- Air-to-surface attack.

Naval surface warfare
- Surface surveillance.
- Antisurface warfare (land and sea targets).
- Antisubmarine warfare.
- Piloting and navigation.

Other airborne
- Offensive bomber.
- ASW and maritime surveillance.
- Reconnaissance.
- Navigation, terrain avoidance, and terrain following.
- Threat warning of missiles.

Other
- Noncooperative target recognition.
- Intelligence.
- Missile range-instrumentation (from both land and ship).
- Drug interdiction.
- Weather radar.
- Aircraft landing.
- Air traffic control.

Civilian Applications of Radar:

Weather
- Nexrad doppler weather radar.
- Terminal doppler weather radar.
- Wind profiler.
- Airborne weather avoidance radar and wind-shear detection.
- Spaceborne tropical rain measurement.

Air-traffic control
- Airport surveillance radar (ASR).
- Air-route surveillance radar (ARSR).
- Airport surface detection equipment (ASDE).
- Weather observation.

Remote sensing of the environment
- Weather (as in the above).
- Mapping of sea ice.
- Measurement of Earth's geoid.
- Ground penetrating radar.
- Oil and gas exploration.
- Earth topography.

Planetary exploration (Venus, Titan, Earth)

Ornithology and entomology

Law enforcement (police speed meter, intrusion detection)

Industrial (distance, speed, and vibration measurement)

Other
- Civil marine radar.
- Remote respiration monitor.
- Sports (speed measurement).

The HF over-the-horizon (OTH) radar was not included in the above since the HF portion of the spectrum is not usually thought of as microwaves. The technology of an HF OTH radar, however, probably would not be strange to a microwave radar engineer. HF OTH radars have been used for long-range aircraft detection (out to approximately 2000 nmi) and for measurement of winds over the ocean surface, but they have also demonstrated capabilities for detection of ships and missiles. Similarly, the microwave engineer would probably feel quite comfortable when dealing with millimeter-wave radar. The frequency boundaries that characterize the microwave radar region have always been somewhat fuzzy and not rigid.

V. Microwaves in Modern Radar

There are three major subsystems to a radar, i.e., the transmitter, which generates the RF power; the antenna, which is the means to couple transmitter and receiver to space; and the signal processor, which selects the desired signals and rejects unwanted echo signals from the natural environment, signals from other electromagnetic radiators, and (in military radars) from hostile jamming. The transmitter and antenna are microwave devices, and microwave engineers have contributed significantly to both. Most of the important accomplishments in radar in recent years, however, have been due to the revolutionary advances in digital signal processing. Although the transmitter and antenna might be thought of by some as "mature" technologies, there are limitations to both that we have come to live with, but which we ought to be able to improve upon.

Digital Processing: Theoretical methods for detecting moving targets in the midst of competing clutter echoes from land, sea, or weather that were only academic curiosities 30 years ago can now be realized in practice because of the availability of digital processing. Human operators peering at a scope display are no longer used to make decisions about target detection, extract information about the target, or perform the tracking of a large number of targets. These tasks, as well as the recognition of one type of target from another, are now performed almost exclusively with digital processing. Furthermore, digital processing usually is not overloaded, as is an operator, when there are more than a few targets that must be processed and some action taken.

An excellent example of the benefits offered by digital processing is the Nexrad doppler weather radar whose output is often displayed as part of a TV weather report. At each resolution cell (range, azimuth, and elevation), Nexrad provides the amplitude, mean radial velocity, and spread in radial velocity to a processor that develops the various weather-related products. The usual TV weather report shows only one of these products—the rainfall intensity on a map-like display. Nexrad digital data processing, however, produces over 30 different weather products [18] that can be displayed to a weather observer, who need not be a university-trained meteorologist.

Digital processing starts by converting an analog signal to a sampled digital signal by means of an A/D converter. As the demands on radar have increased, the amount of information that has to be processed digitally has increased so that some modern radar applications require A/D converters with sampling rates (bandwidths) of many hundreds of megahertz, or even more than a gigahertz. Ideally, the A/D converter should be right at the antenna to convert the RF signal directly to digits, but we are probably a long way from this for most microwave radar applications. Thus, A/D converters and digital processing are beginning to appear at frequencies that have been considered to be microwaves. Even desk top PCs run at microwave rates. The microwave engineer has always appreciated that the transmitter and antenna of a radar require the application of microwave theory and techniques for success, but the digital processor of some radars is also impinging on the realm of microwaves. It is expected that advancement in radar performance and applications will continue to be driven in the coming years in large part by the benefits offered by improved digital processing. (It might be mentioned that, in some radars in the past, the signal and data processor have occupied more volume, been heavier, and required more power than the transmitter.)

Transmitters: There are several different types of transmitters available to the radar systems engineer, depending on the application. The klystron is a good choice for high-power applications, with the TWT as a candidate when wide bandwidth is needed. The magnetron, which made microwave radar so successful in World War II, is no longer a viable candidate for high-power applications or when good doppler processing is required to see moving targets in heavy clutter backgrounds. However, it is still the transmitter of choice for the inexpensive civil marine radar, which requires neither high power, nor doppler processing. In military applications, the solid-state device has been popular. (Many radar program managers often demand solid-state transmitters from the manufacturer without really understanding its limitations on the radar system.) Solid state is an excellent choice in low-power systems such as FM-CW radar altimeters or when very wide bandwidth is required. Solid state does, however, have some serious system limitations when high power is required. Its need to operate at high duty cycles requires long pulses (in some systems, as long as 1 ms) so that pulse compression must be used for good range resolution. Also, multiple waveforms with different pulsewidths are needed in order to detect targets at short ranges that are masked by the longer duration pulses. These limitations, as well as its lower transmitter efficiency, tend to offset the more favorable aspects of solid state in some applications. (The added cost to accommodate pulse compression, multiple waveforms, and the lower transmitter efficiency is usually not charged to the solid-state transmitter, even though it often results in a larger total radar system cost.)

Aside from solid state, there have been only a small number of new developments in transmitter technology in recent years. One reason is that transmitter engineers have been retiring and have not been replaced. Another reason is that transmitter research is of little interest to academic research laboratories since it is not new and exciting to them. The current options for radar transmitters have been able to do the job asked, but additional efforts are needed to explore new possibilities for generating high RF power or improving the capabilities of current methods. An example of a relatively new and important radar transmitter development is the so-called clustered-cavity klystron [19], which employs a different type of resonant cavity to provide a broad-bandwidth high-power klystron with good efficiency—far better than other klystrons or high-power TWTs.

Antennas: The electronically steered phased array seems to be the antenna currently favored by many military radar program managers. The phased array is well suited for air-defense battle management, but is less attractive for long-range air-surveillance applications. In spite of its important advantages, it has some limitations that should not be ignored. These include its high cost, limited scan angle per face, software complexities, change of polarization with scan angle (which is a consideration for some applications), and difficulty in achieving wide signal-bandwidth operation. These limitations are reasons why continued research and development is important for improving the phased-array radar.

An advantage of a phased array is its ability to perform multiple functions (such as surveillance and weapon control) with a single system. However, multiple functions are best performed when each function enjoys the same optimum frequency. (For example, long range air surveillance is best performed at L-band and weapon control is best performed at X-band. When a single frequency is used for both functions, a compromise frequency has to be selected where neither function has its maximum efficiency.) Sometimes multiple radars performing dedicated functions are better (and maybe cheaper) than one multifunction radar at a single frequency that does not permit sufficient time for each function to be carried out effectively [20]. Operation at a single frequency also increases the radar's vulnerability to electronic countermeasures.

An "active aperture" is an electronically steered phased-array radar where each element of the array has a transmit/receive (T/R) module with its own solid-state transmitter, receiver, phase shifter, and duplexer. That is, a miniature radar is at each antenna element. This array architecture is currently quite popular for military applications since it avoids the large loss that can occur in the power-dividing networks when a single high-power transmitter is used. (This loss does not occur, however, when a single high-power transmitter is used with a space-fed phased array.) As with most things in life, the active aperture has its advantages and its disadvantages, thus, one should consider all viable radar architectures before making a selection.

There have been efforts to reduce the cost of a phased-array radar based on the Radant approach [21], ferroelectric phase shifters [22], and microelectromechanical (MEM) switches [23].

Other Microwave Components: In addition to the development of improved T/R modules for active aperture radars, as well as improved transmitters and antennas, microwave engineers provide various other microwave components needed for effective radars. These include duplexers, receiver protectors, circulators, RF sensitivity-time-control networks, mechanical rotary joints for the antenna, microwave low-noise transistors for the receiver front end, surface-acoustic wave (SAW) dispersive delay lines for high-resolution pulse compression, and phase shifters and other microwave hardware for phased-array radars.

Electromagnetics: The well-known equations of Maxwell, which date to the early 1860s, is the heart of electromagnetics theory. In radar, Maxwell's equations provide the basis for calculating the radar scattering from aircraft, ships, and missiles, as well as the radiation from antennas. Until recent times, however, Maxwell's equations were mainly of academic interest. They could not be readily solved, except for relatively simple shape scattering objects and a limited number of antenna types. However, with the improving hardware and software capabilities of modern digital computers beginning approximately 30 years ago, the radar engineer can now apply numerical computation methods to obtain useful solutions to Maxwell's equations for scattering from complex objects and for radiation from antennas. Numerical computation is probably the best method (experimental, as well as theoretical) for determining the precise nature of radar scattering from complex targets such as ships and aircraft. Much of the incentive for the computer calculation of scattering was due to the need to understand the design of military aircraft that have low radar cross section (low radar backscatter) [24]. Thus, the needs of military radar have helped accelerate the application of digital computers so as to provide a highly useful microwave engineering design tool to deal with Maxwell's equations.

VI. Possible Future Directions for Radar

Military Systems: The need for radar for military applications has not decreased. Current military air-defense radars such as those employed in Aegis, Patriot, AWACS, and the E2C AEW were all conceived approximately 40 years ago. Over the years, they have been upgraded with new component and software technology, but these systems will soon need replacing. Military threats have increased since these systems were first introduced; hence, the systems that replace them should be quite different from what is now current. In addition, it is likely that the following could help drive future radar developments:

- airborne battlefield surveillance in aircraft smaller than those now employed for JSTARS;
- the use of unmanned aircraft (UAVs) for surveillance and the need for battlefield air-defense systems to negate the effectiveness of hostile UAVs;
- the continuing need for maintaining highly reliable combat identification;
- extension of the radar horizon by means of improved HF radar (for very long ranges) or a relatively simple elevated planar reflector (for short and moderate ranges);
- the desire to provide some measure of ballistic missile defense;
- the need to counter the continual improvements in electronic warfare measures designed to degrade radar;
- the need for radar to perform its missions when the targets are of reduced cross section.

If the past is any guide, it is likely that future radar systems will be strongly affected by new unexpected threats and new unexpected advances in technology that are not on the current "radar screens" of military planers.

The above should insure that there will be much that needs to be accomplished by military radar engineers in the coming years (so long as Congress, the Department of Defense (DoD), and the public agree).

Civil Systems: The chief accomplishment in civilian radar in recent years has been the considerable improvement in weather radars, especially their use for obtaining weather information based on the doppler frequency shift (which provides a measurement of radial velocity). The weather radar community is currently looking at possible replacements for these radars and for new weather radar concepts for the future.

Technology: The major accomplishments in radar in recent years have been due to the tremendous advances in digital technology, especially digital technology that originated in the commercial sector. It is expected that significant advances in digital technology and their application for enhanced radar will continue. There is certainly a need for improved RF power sources for radar and improved antennas; but these are less likely to be funded than developments based on the more glamorous digital technology.

Sea Echo [25]: Radar backscatter from the sea has been investigated ever since the beginnings of radar in World War II, yet we still do not fully understand the mechanism of microwave radar sea echo. Many theoretical concepts have been proposed in the past to explain microwave sea echo, but they have all been lacking. Some microwave sea clutter theorists still cling to the Bragg scatter model for describing microwave sea clutter. Bragg scatter is a good model for sea echo at HF and VHF frequencies, but not at the higher microwave frequencies [26]. The Bragg theoretical model is based on unrealistic assumptions. Furthermore, observations of the sea with high-resolution radar are not consistent with the Bragg model. It has been found experimentally that the microwave sea echo is due to short duration (1 s or a few seconds) sea spikes that appear nonuniformly in time and space. Sooner or later, the radar community will have to realize that the sea spike model, rather than the Bragg model, represents the true nature of microwave sea echo. There is an opportunity for a major advance in understanding microwave sea echo, but it is not a subject that seems to attract sponsors of basic electromagnetic research.

Two Examples of New Opportunities: There are two new radar concepts on the (technological) horizon that could have major influence on future systems. Both have been considered in the past, but were found wanting because of the lack of adequate technology and/or the lack of useful applications. Technology advances now make both of the concepts feasible and much more desirable than in the past. One is the phased array with fixed beams that look everywhere all the time (ubiquitous), and the other is high-power millimeter-wave radar.

Ubiquitous Radar: This is a radar that looks everywhere all the time, and in so doing, has important advantages over conventional scanning radars [27]. It uses a receiving phased-array antenna with multiple fixed contiguous directive beams. The transmitting antenna has a broad quasi-omnidirectional radiation pattern, which covers the same volume as the multiple beams of the receiving antenna. On receive, the signal at each element of the array is converted to digital format and multiple beams are formed in a digital beam former (DBF). The output of the DBF is a number of fixed independent receiving beams. At each beam there are one or more digital signal processors for simultaneously accomplishing, in parallel, the various required radar functions. In a military air-defense radar, these functions might include: 1) long-range low data-rate (long revisit time) air-surveillance; 2) short-range moderate data rate air-surveillance for targets that "pop up" at low altitude as they appear at the radar horizon; 3) high data-rate weapon control; and 4) noncooperative target recognition. Each of these functions can use the same waveform with the same pulse repetition frequency and pulsewidth, but they employ different integration (or revisit) times, different signal processing, and operate over different ranges. In a civil air-traffic control application, a ubiquitous radar can simultaneously perform the functions of aircraft detection and tracking, weather observation, and warning of dangerous wind shear. The chief advantage of a ubiquitous radar with digital beamforming and digital signal processing is that it can perform multiple functions *concurrently*, whereas conventional multifunction phased-array radars have to perform their different functions *one at a time*. Time sharing in a conventional phased array means that when the target traffic is large, some functions have to be delayed—with a consequent loss in overall system effectiveness. The ubiquitous radar has no such limitation. Its success depends on the ability to perform the required digital processing. There are many other interesting benefits of a ubiquitous radar that cannot be included here in this introductory discussion [28], [29].

Millimeter-Wave Radar: For almost 50 years, it has been said that millimeter radar will be the new frontier or that "it is just around the corner." This has not yet materialized since the technology at millimeter waves has been seriously lacking (especially high power) and there have been few, if any, applications where millimeter-wave radar is better suited than microwave radar. (By mentioning this subject in this paper, I am assuming that most microwave engineers would not hesitate to embark on the development of millimeter-wave radar if the challenge were worthwhile, which I think it now is.) There has been progress in both the technology and in the identification of worthy applications.

High-power gyrotrons as a source of millimeter-wave power were developed many years ago by the Soviet Union, but it has only been recently that such power tubes have been available for consideration in radar applications [30]. An experimental pulsed W-band (94 GHz) gyroklystron delivered an average power of 10 kW (a very respectable radar power at any frequency) and a peak power of about 100 kW [31], [32]. A radar with such a tube is capable of fitting into a mobile trailer. Millimeter-wave radar applications include noncooperative target recognition, counters to air-defense threats, and the investigation of the nature of clouds. Ever since the first observation of millimeter waves in 1895, there has been the desire to apply this part of the frequency spectrum to some useful applications. The technology and potential applications have now advanced to the point where millimeter-wave radars can be seriously considered.

The Future: There is reason to expect that microwave radar will continue to be important for both military and civilian applications. It has the potential to grow. This is even more true if microwave engineers interest themselves in radars that operate outside the normal microwave radar frequencies (usually considered in the U.S. to be from UHF to K_a-band), as well as recognize the importance of digital processing techniques operating with clock rates that are at microwave frequencies. Near-term advances in radar will likely be dominated by advances in digital processing. Radar applications could also benefit considerably by increased attention to: 1) improving RF power sources (in efficiency, average power, stability, reliability, duty cycle, and affordability); 2) antennas, including new phased-array concepts, as well as exploiting the advantages of endfire antennas for some applications; and 3) making it easier to operate phased-array radars with increasingly sophisticated digital processing and digital control. It is likely that the ubiquitous radar will be the architecture used in future sophisticated phased-array radar systems. As military radars continue to perform their missions well, there will also be the need to counter the many earnest attempts to degrade military radar performance by countermeasures, stealth, and other hostile actions. Weather radars made a significant advance in the 1990s, and this is expected to continue and grow.

As indicated at the beginning of this paper, advances in microwaves continue to allow radar engineers to achieve improved capabilities, and advances in radar applications continue to require microwave technology for their success. Radar and microwaves have been, and will continue to be, a great match.

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