Opportunities in radar—2002

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This paper addresses some of the potential opportunities for achieving advances in radar systems and technology. It is not a summary of current interests in radar, nor is it a forecast of what 'will be', but is speculation about what 'could be' based on the limited experiences and personal biases of the writer. Included are the replacement of existing radars that have been in use for some time, 'on-the-shelf' concepts and demonstrated technology that have yet to be employed, a few new directions that might offer capabilities that do not currently exist, and areas of basic technology that could be further explored to provide new understanding and new capabilities. Although much is included in the paper, it is not meant to be an exhaustive enumeration of the many possible directions for future radar.

1 Introduction

Ever since its appearance just before the beginning of World War II (WWII), radar has had a significant effect on military air defence and other military missions. The technology and application of radar developed rapidly as a result of the needs of WWII, and growth has been continual ever since. At the start of WWII, in 1939, most radars operated at VHF frequencies (usually 100 and 200 MHz). VHF was the frontier of radio technology at that time. The successful development by the British of the high-power cavity magnetron at 10 cm wavelength (S band) in 1940[1] allowed radar to push the frontiers even further, into the microwave region. At the MIT (Massachusetts Institute of Technology) Radiation Laboratory in the USA, over 100 different microwave radars were developed before the war ended[2]. Although there have been a large number of innovations and new capabilities introduced for radar, a short list of the major factors affecting radar might be represented by the following:

- The coming of the *long-range heavy bomber* in the early 1930s, which lead many military leaders of the time to say 'the bomber will always get through'. The threat of the bomber was the incentive to develop radar to provide long-range warning and information that allowed the effective interception of the attackers, as was demonstrated in the Battle of Britain in 1940.
- The *high-power cavity magnetron*, which allowed microwave radar to be a reality. Microwave radar has an advantage over VHF or UHF radar in that the antennas can be much smaller, allowing the radar to be used in aircraft and in mobile ground systems. (It is interesting to note that the Japanese and the Russians also discovered the cavity magnetron in the late 1930s before the British did, but their military did not appreciate its value. The British, as well as the US, success with the magnetron in WWII has been attributed, in part, to their radar programmes being managed by civilians rather than by the military, as it was in the totalitarian countries.)
- The *high-power klystron amplifier* that appeared in the 1950s allowed much greater power and better stability (needed to detect small moving targets in heavy clutter) than can be obtained from a magnetron. Although the magnetron was the RF power generator that originally made microwave radar possible, it has been almost entirely replaced in radar by the klystron amplifier where high power and good stability are required.
- The detection of small moving targets in heavy clutter has been made possible by taking advantage of the *Doppler frequency shift* of moving targets to separate moving from stationary (clutter) targets. None of the operational pulse radars in WWII used the Doppler effect since aircraft generally flew at high altitude well above the ground or sea clutter. After the war it was realised that aircraft had to fly at low altitude where the radar echo from clutter would mask the aircraft's radar echo. The major advances in radar after WWII have been mainly in the use of the Doppler shift from moving targets. In military applications this includes the MTI (Moving Target Indication) radar and the pulse Doppler radar. The extraction of the Doppler frequency shift also has had a major effect in improving the capabilities of weather observation by measuring wind and wind shear.
- Perhaps the most significant advance in radar in the past 30 years has been the application of *digital technology* to allow the radar designer to make practical what in the past were only academic curiosities. The ability to detect moving targets in clutter, the automatic detection and tracking of large numbers of aircraft for either military air defence or civil air-traffic control, and the recognition of one type of target from another are among the capabilities that would not have occurred without the revolutionary advances in digital technology.

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No matter how many accomplishments that might have been made in the past in any particular technical field, the question is always asked 'So, what else can you do *now*?' Although there are those who like to forecast the future (there have been consultants and companies that specialise in this endeavour), experience shows that predictions of what will occur in the future (beyond the next 3 to 5 years) are usually doomed to failure. Almost all of the major advances in radar in the past have come as surprises. Therefore, instead of forecasting what will be in radar, this paper speculates on what 'could be' in radar. The discussion will be divided into four categories: (1) replacement of current systems, (2) existing 'on-the-shelf' technologies not applied to their fullest, (3) new directions in system concepts, and (4) opportunities in technology. Because any writer is limited by his or her own experiences, background, and personal biases, the point of view in this paper is that of an individual US radar systems engineer and does not attempt to provide an exhaustive world-wide view of current radar interests nor the entire set of opportunities that might be available in the field of radar.

2 Replacement or upgrading of current radar systems

Military air defence

Current military air defence ground-based radar systems such as the US Army Patriot and the US Navy Aegis, as well as airborne air-surveillance radars such as the US Air Force AWACS and the US Navy AEW (E2C) were all conceived in the 1960s. The requirements for these systems reflected the military threats that existed at that time, which were mainly concerned with manned aircraft. It is not likely they took into account the threat from cruise missiles, sea-skimming missiles, ballistic missiles, reduced cross-section targets, or antiradiation missiles. As time went on and these new threats arose and new technology became available, the already fielded radar systems were upgraded to take advantage of new technology and to combat new threats. The basic character of these systems, however, remained relatively unchanged. When current systems will eventually have to be replaced, there will be an opportunity to introduce new system concepts and architectures, as well as new technology for improved systems that have to exist as long as 30 to 40 years after their initial deployment (which might be 10 to 15 years after the new system is first conceived).

Any military system that is successful attracts hostile countermeasures designed to reduce or eliminate its effectiveness. Thus military radar has to be continuously upgraded in order to cope with the many forms of electronic warfare measures and anything else that might threaten a military radar's success. Radar designers have learned how to deal with the adverse effects that the natural environment has on radars. If the natural environment were the only problem facing military radars there would not be much to do. It is the ever-changing threat of potential hostile actions that keeps military radar engineers busy creating new capabilities that can allow radar to fulfil its mission in spite of hostile measures.

As missiles and UAVs (Unmanned Aerial Vehicles) have begun to dominate the battlefield, it is no longer sufficient simply to shoot at the missile or other weapon fired at a target. If an attacking missile is destroyed today another can be expected tomorrow (if not sooner). Air defence in the future will have to engage the launch platforms and the people that send out the missile so that the attackers don't keep on coming until they finally succeed. New radar and weapons system concepts are needed to put the hostile 'manned' resources at risk rather than just the 'bullets'. (It might be recalled that in WWII the Japanese ran out of experienced pilots before they ran out of aircraft.)

HF over-the-horizon (OTH) radar

This is a radar that extends the detection range an order of magnitude beyond that of microwave radars (coverage extending from 500 to about 2000 nautical miles (nmi)). Although HF OTH radars are large and expensive, they cost much less than microwave radars that provide the same coverage. The Australians successfully use OTH radars for surveillance of the waters outside their large and sparsely populated coastline. The US Navy employs the ROTHR (Relocatable Over-The-Horizon Radar) to provide surveillance of the vast region south of the US that has been used by airborne drug traffic. The technology of the US and Australian systems is based on the FM-CW radar, which requires wide spacing (about 100 nmi) between receiving and transmitting sites. FM-CW is an old and cumbersome radar architecture for high-performance radar. A pulse OTH radar at a single site is quite feasible; it has more flexibility than a CW system, and would be of lower cost than current operational systems that need two separate sites. In addition to this major change in architecture, an OTH radar can be operated from a ship so as to be truly relocatable to provide coverage over a large region, an important need for military air-surveillance. (One doesn't need mile-long antennas for aircraft detection by OTH radar.) Such a radar can provide coverage well beyond the battlefield and would be of value for amphibious operations. A relatively simple single-site OTH system can be used to provide the over-ocean wind speed and direction over ocean areas greater than 10 million square miles for the purpose of weather observation in regions of the world where weather observations are difficult to make. (The Australian OTH radar already provides such information as a by-product of its prime mission.) It was the availability of modern digital processing that made the OTH radar a practical reality 30 years ago, and improved digital processing can provide even greater capabilities.

Weather radar

It might be said that the most significant advance in radar that occurred during the 1990s was in weather radars. These include Nexrad, Terminal Doppler Weather Radar (located near airports), Wind Profiler, Tropical Rainfall Measuring Mission (a spaceborne radar), and airborne Doppler weather radars to detect dangerous wind shear on landing or taking off. It took a long time for the radar meteorologist to include the Doppler frequency shift in

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weather radars, and much of the technology needed had its roots in previous military developments. Doppler weather radars will continue to be an important part of weather observation and research. A recent study[3] has outlined the directions future weather radars might take.

Smaller battlefield surveillance systems

Joint STARS is a battlefield surveillance radar that provides a high-resolution SAR (Synthetic Aperture Radar) image of a scene along with indication of moving targets superimposed on the same scene. (The moving-target detection mode is sometimes known as GMTI.) SAR/GMTI in the Joint STARS system was first demonstrated in battle during Operation Desert Storm. It is a very capable radar that assists the important military mission of surveillance of the battlefield. Originally this radar was designed by the US Army for small aircraft. When the US Air Force took over the programme it enlarged the system to fly in a Boeing 707 aircraft. There are some military missions where a small aircraft or UAV may be a better choice than an expensive and vulnerable aircraft. The same company that developed Joint STARS also developed in the early 1990s the AN/APG-76, a much smaller radar than Joint STARS with SAR, interferometric GMTI, and other capabilities suitable for use in an attack aircraft[4]. In the future a battlefield surveillance capability with missions similar to those of Joint STARS might be more likely to be found as part of a UAV or a fighter/attack aircraft.

3 Existing, not yet applied, 'on-the-shelf' capabilities

In research and development that seeks new capabilities, many ideas and concepts are examined or actually developed, but few see application. There may be good reasons for this. There are, however, several unexploited ideas in radar that have been demonstrated but not seen application and that should probably be considered further. Two are mentioned here.

Elevated reflectors

Ever since the airborne attacker realised that one had to fly under the radar coverage to avoid detection, there have been various attempts by the defence to extend the coverage of radar to allow detection of low flyers. This is the purpose of putting a long-range air surveillance radar in an aircraft. It increases out to 200 nmi, or more, the 10 to 15 mile horizon range of a surface radar against a low-altitude target. This approach has been quite successful. In addition to the US Navy E2C and the US Air Force AWACS radar aircraft, airborne air-surveillance radars have been developed by the Soviet Union, Sweden, and Israel in addition to the Wedgetail developed by the USA (Boeing and Northrop Grumman) for Australia. These developments indicate the need for and the popularity of radars that can extend the horizon. The HF OTH radar is another example of extending the radar horizon, as is the use of an aerostat to hoist the radar to a moderate altitude. Large aircraft carrying air-surveillance radars, however, have some disadvantages. They are of high cost and can be vulnerable to attack. In addition, if one wants to have an airborne radar available in operation all the time there must be more than one aircraft. A rough 'rule of thumb' is that five aircraft are needed in order to ensure that there is at least one aircraft operating on station. This further increases the cost of airborne systems.

A radar in an aerostat has sometimes been considered as a means to extend radar coverage. Such a radar can be more vulnerable to attack than a mobile ground-based system, it has limited coverage compared to an airborne radar, and it cannot operate in some types of weather situations. (The aerostat approach was attempted by the USA for interception of airborne drug smugglers along the southern coast of the USA, but it had only limited success.) When it is necessary to extend the radar horizon of a ground-based radar faced with low-altitude aircraft or missile targets to almost 60 nmi a simpler approach can be used. This is to employ an elevated rotating planar reflector (a mirror) in a small aerostat with a surface-based radar whose beam is directed up and then reflected by the rotating tilted mirror to extend beyond the horizon of the surface-based radar. In one particular experimental embodiment a 7 by 10 ft rotating mirror was mounted in a very small aerostat at a height of 500 ft. A conventional X-band radar with one-degree beamwidth illuminated the mirror, which redirected the beam out to a range of almost 30 nmi (assuming a target at a height of 10 ft above the surface of the sea). The experimental equipment in the aerostat weighed less than 200 pounds. A transmission line carried 1·5 kW of prime power up to the aerostat. A 10 by 14 ft mirror at an altitude of 860 ft can have a horizon of about 40 nmi, and a 15 by 21 ft mirror at an altitude of about 2000 ft can extend the horizon out to almost 60 nmi. Compared to a full radar in an elevated aerostat, the advantages of the elevated mirror are that there is much less weight and power to be carried by the small aerostat, and if hostile action destroyed the elevated mirror it would be far simpler, less costly, and much quicker to launch another lightweight mirror aerostat than to replace an entire aerostat radar.

Wide-band air-surveillance radar

It is not possible to guarantee that a radar will be impervious to hostile electronic countermeasures. A determined offence willing to pay a high enough price can always penetrate a defence. But on the other hand, there are some things a military radar designer can do to significantly reduce the vulnerability of a radar. An example is the experimental Naval Research Laboratory radar known as Senrad[5], which was designed to make hostile noise jamming as difficult as practicable.

The chief tactic was to operate the radar within a wide bandwidth. On each transmission the radar radiated simultaneously within the bands from 850 to 942 MHz and from 1215 to 1400 MHz. (It had the capability to radiate anywhere from 850 to 1400 MHz, but there were other users of the spectrum, which precluded its operating outside the usual radar bands.) Thus a jammer would have to dilute its energy by spreading the jamming power over the wide bandwidth that the radar utilises. As the antenna scanned by a target it would radiate a minimum of four

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long-range pulses and four sets of three MTI pulses. The three MTI pulses had to be at the same frequency, but there could be four different long-range frequencies and four different sets of three MTI pulses radiated on each of the two sub-bands. The result was that at least eight different frequencies could be radiated on each scan. The individual frequencies could be changed from scan to scan. (Actually the lower sub-band antenna had a slightly wider beamwidth than the higher sub-band antenna so it could radiate more than the eight different frequencies.)

The antenna had low sidelobes and rotated at 15 rpm. In addition to its advantages in combating ECM (Electronic Counter Measures), the Senrad concept of radiating multiple frequencies allowed better automatic tracking (since there were no deep nulls in the composite elevation radiation pattern to cause the loss of a target track). The use of multiple frequencies allowed MTI without blind speeds (the multiple frequencies performed the same rôle as multiple pulse repetition frequencies in an MTI radar to avoid blind speeds). Using a fan-beam antenna, the wide bandwidth of this radar allowed target height-finding over the sea (and perhaps over land if the surface contour was known) based on the time difference between the multipath signals. Wide bandwidth also permitted an approximate form of perceptual target classification (separation into large jet, small jet, large propeller aircraft, small propeller aircraft, helicopter, missile, and decoy). Although it was not a consequence of the wide bandwidth, Senrad also demonstrated the ability of the radar signals to be used to directly communicate its processed information to other radars. Senrad was quite different from current radars and could form the model for future military air-surveillance radar systems with capabilities not now available.

4 Possible new directions

Two new directions that will be mentioned here are (1) the use of digital beam forming for achieving an ubiquitous radar with properties and capabilities not available with current phased-array system architectures and (2) high-power millimetre wave radar for applications better suited for millimetre waves than for microwave frequencies.

Ubiquitous radar[6]

In the 1960s there was interest in radars that utilised a large number of highly directive contiguous receive beams and a broad transmitting beam from a low-gain antenna covering the same volume of space[7]. The Butler beam-forming network or other analogue multiple-beam-forming networks were usually used[8]. After a brief burst of activity, the interest in such radar architectures quickly faded. The analogue hardware was quite cumbersome and there were no obvious applications where multiple fixed beams appeared to have an advantage over the conventional scanning single-beam radar. Recently, however, there has been interest in radars with multiple fixed receiving beams and a single broad transmitting beam since their implementation using digital beam forming is easier than when using analogue methods; it offers more flexibility than analogue beam forming, and there are now applications for such a radar that cannot readily be obtained with a conventional radar architecture. For military radars, the two applications now achievable with digital beam forming are (1) multifunction phased arrays in which the various functions are performed *simultaneously* instead of in sequence (one at a time) and (2) a low probability-of-intercept radar that spreads its energy in the spatial, temporal, and spectral domains so as to reduce significantly the peak power radiated by the radar. A radar that uses multiple directive fixed receiving beams occupying the full coverage is one that looks everywhere all the time, which is why it is called here an *ubiquitous radar*.

Consider a linear phased array of N elements. Instead of a phase shifter at each element, there is a receiver with an analogue-to-digital converter. In a digital beam-forming array, the digital outputs of each element are processed to form N contiguous beams in a manner analogous to forming a filter bank with N filters. The stream of digits from each beam position is processed independently of the other beam positions to perform Doppler filtering or other radar functions with different revisit (or integration) times.

Simultaneous multiple functions: To illustrate the operation of a radar that can perform simultaneous multiple functions, first consider a radar that doesn't. This might be a conventional scanning radar designed to detect a target with a one-square metre radar cross-section at a range of 140 nmi with a revisit time of 4 s, as might be employed for an aircraft surveillance mode. The dwell time, or time on target, when the antenna has a 1·5 degree beamwidth is 16·7 ms. Now consider a digital beam forming (DBF) air-surveillance radar with 240 fixed 1·5 degree receiving beams covering 360 degrees (perhaps made up of four separate apertures). For comparable performance, the DBF radar has to coherently integrate for four seconds rather than 16·7 ms. Such a long integration time is difficult to do with analogue signal processing but can be achieved with digital processing. As the range of the aircraft target decreases, the echo signal power increases inversely as the fourth power of the range. In conventional radars, sensitivity time control (STC), or swept gain, is used to reduce the wide variation of the received signal power with range. In the DBF radar, however, STC is not used. Instead, the number of pulses integrated (or processed) is decreased as the target range decreases so as to maintain a sensitivity roughly independent of range. With coherent integration the revisit time (or data rate) in this example can then be 1·0 s at 100 nmi, 0·25 s at 70 nmi, and 0·1 s at 55 nmi (a 0·1 s data rate is often used to track targets for the purpose of weapon control). Based on the above assumptions, a 10^{-4} m^2 target (the size of a large insect such as a locust) can be detected at 10 nmi with a one-second revisit time.

At ranges longer than 140 nmi, a longer revisit time than 4 s can be tolerated since operations do not occur as fast at the long ranges. With 20 s of coherent integration time the range on a 1 m^2 target is 209 nmi. (With noncoherent integration or a combination of coherent and noncoherent integration, the ranges are lower for the

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same number of pulses processed.) Thus the DBF radar operating as indicated above can perform simultaneously long-range surveillance with a low data rate, medium-range surveillance at a high data rate, and air defence engagement at suitable ranges with a high data rate. This requires, however, a level of digital processing not now employed in current radars.

Since the antenna beams are fixed (nonscanning) and look everywhere all at once, all of the radar functions can be performed in parallel in separate signal processors at the same time. There is no need to time-share multiple functions as there is in a conventional multifunction phased array. In parallel, there can also be processing for non-cooperative target recognition and for burn-through of jamming signals without taking time from other radar functions.

Any multifunction radar that operates within one frequency band has to accept serious compromises when each of the functions is best performed at different frequencies. For example, in a shipboard air defence radar system, long-range search is best performed at the lower frequencies (usually L band), close-in defence against low-altitude short-range pop-up targets is best performed at higher frequencies (such as X band), weapon control is not usually performed at frequencies lower than S band, and missile guidance is usually found at X band or higher. Thus any single frequency-band multifunction air defence system, whether of ubiquitous or conventional phased-array architecture, has to accept compromises compared to the use of separate radars operating at their optimum frequencies. On the other hand, all the multiple functions of an HF over-the-horizon radar are performed within the same frequency band, so that no compromise has to be made for multifunction employment.

Low probability of intercept (LPI): The basic philosophy in designing a radar to have a low probability of being detected by a hostile intercept receiver is to reduce the radar's peak power. An intercept receiver is designed to detect the radar's peak power (since it usually cannot rely on prior knowledge of the radar signal's waveform). A radar, however, uses a receiver with a matched filter designed for the specific waveform transmitted, which makes it an efficient signal-waveform detector. To reduce the radar's peak power, but not its total energy, the signal energy can be spread over time (a high duty factor), frequency (use of spread spectrum or multiple simultaneous frequencies over one or more radar bands), and space (a quasi-omni transmitting antenna with multiple fixed receiving beams). Conventional radars that utilise a highly directional scanning transmit-receive beam cannot utilise all three domains to spread their radiated energy, but the DBF ubiquitous radar can. Rough (very approximate) estimates for the DBF ubiquitous radar indicate that it might be possible to reduce its peak power by a factor that might extend from 10^4 to 10^9 depending on the assumptions made[9]. A reduction of a million to one might be a ratio to think of as a goal, which could cause problems with many current electronic warfare receiving systems.

Height finding with a DBF ubiquitous radar: For simplicity, the previous discussion assumed a linear array generating multiple contiguous fan beams. A DBF receiving antenna might utilise a two dimensional (azimuth and elevation angle) phased array that fills the volume to be covered with a large number of directive pencil beams. A wide-beam, low-gain transmitting antenna illuminates the same region. A radar with an array of pencil beams would be more complicated than a linear array that generates fan beams, so one might not want to embark on a two dimensional DBF ubiquitous array until having gained experience with a one dimensional system.

A simpler method for obtaining both the azimuth and elevation angles is to employ two linear arrays. One would be a horizontal linear array of fan beams that provides the azimuth angle as assumed previously. The other would be a vertical linear array that generates a number of contiguous conical beams to provide a measurement of elevation angle. Note that the fan beams of the horizontal linear array that obtain the azimuth angle are actually portions of a conical beam when scanned in angle. At broadside the beam is a vertical fan beam, but as the antenna is scanned from broadside the fan beam becomes increasingly conical. Thus the angle to which the vertical beam is steered is not the true azimuth angle of the target. The correct azimuth can be found, however, from knowledge of the elevation angle measured by the vertical array producing conical beams.

There are many other things that can be said about the DBF ubiquitous radar, its properties, interesting attributes, limitations, technical challenges, and applications, as can be found in a Naval Research Laboratory report[9] on this subject and the many references cited in that report.

HF OTH radar, a potential application of ubiquitous radar: HF over-the-horizon radars can detect aircraft and helicopters, ships, and ballistic missiles, as well as determine ocean wind speed and direction. Detection for each of these capabilities requires a waveform with a different dwell time (time on target) and a different revisit time. Current HF OTH radars have to perform these various functions one at a time. On the other hand, a DBF ubiquitous HF OTH radar can perform these simultaneously rather than sequentially.

The US Navy's ROTHR[10], developed in the late 1980s, already employs digital beam forming to generate 16 contiguous receiving beams. A separate wide-angle transmitting beam has the same coverage as the 16 receiving beams. ROTHR was an early application of digital beam forming, perhaps because DBF is easier to accomplish at HF than at microwave frequencies and the parallel beams can provide a shorter revisit time than if only a single scanning beam were used. ROTHR is not a ubiquitous radar, however, since its 16 beams are stepped together in azimuth over eight sectors to provide 60 degrees of total azimuth coverage. The step scanning does not allow simultaneous multiple functions to be obtained, but it seems it would be relatively straightforward to increase the number of receiving beams to perform simultaneously all the functions that might be performed by an OTH radar system.

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Millimetre wave radar

Millimetre wave electromagnetics were first investigated in 1895[11], shortly after the first 'microwave' investigations of Heinrich Hertz in the late 1880s. Following the success of microwaves in the 1940s, millimetre waves were said to be the 'next frontier' and 'just around the corner'. They didn't develop as hoped because:

(*a*) there were no reliable sources of high-power millimetre wave energy (although there were tubes that were supposed to provide a few hundred watts of average power, only a few watts or a few tens of watts could be relied upon)
(*b*) receiver noise figures were quite high (25 dB was not unusual)
(*c*) transmission lines and components were lossy and not capable of handling high power
(*d*) there were no important applications that were better performed at millimetre wavelengths than at other portions of the electromagnetic spectrum, and
(*e*) the losses in propagating through the clear atmosphere were large[12].

Except for the propagation losses, all of these limitations seem to have been overcome. There are sources of high millimetre wave power; the noise figures are not as low as at microwaves, but they are respectful; quasi-optical transmission lines are available with more power handling capability than conventional waveguides; and there are applications suited to millimetre waves. Two potential applications are: (*a*) the non-cooperative recognition of aircraft based on ISAR (Inverse SAR), which should be an order of magnitude better at W band (3 mm wavelength) than at X band (3 cm wavelength) since it takes only one-tenth of the change in target aspect at W band to produce an image with a given resolution than at X band; and (*b*) the cross-section of targets should be higher at W band than at X band and there can be more scattering centres for better recognition. In the past, low power millimetre wave radars have been of interest for observation of the natural environment. The high-power millimetre-wave radars now becoming available should therefore also be of interest for similar scientific explorations.

An example of a high-power transportable experimental W-band radar is under development and testing at the Naval Research Laboratory in Washington, DC[13]. It has a 6 ft diameter antenna and a gyroklystron amplifier that delivers an average power of 10 kW with a peak power of about 100 kW[14].

5 Technology

Most of the 'opportunities' mentioned previously in this paper have been concerned with the applications of radar. It is the application that provides the *pull* to develop new radar concepts and capabilities, but it is the realisation of new technology that is the *push*. Many past advances in radar have been obtained by taking advantage of advances in technology made for other areas of electrical engineering. Digital technology is an important example.

Digits

The first major example of the application of digital technology to radar was the US Air Force SAGE (Semi-Automatic Ground Environment) system, a military system developed in the late 1950s for automatically combining the data from a number of air-surveillance radars and providing tracking of the aircraft environment for purposes of air defence. The computers for the SAGE system used vacuum tubes, filled a large warehouse-type building and required a number of hours scheduled down-time each day for preventive maintenance. The world of digital technology has come a long way since then because of the advances in solid-state technology. It is probably reasonable to say that the major accomplishments in radar capability in recent times were made possible by the revolution in digital computer technology that began in the early 1970s—and is still going on. It is expected that the significant contributions to radar by the advances in digital methods will continue and significantly affect signal processing, data processing, information extraction, and automatic control of the radar's functions.

RF power generation

RF power is an important part of a radar system. The transmitter must generate the high energy needed for good detection and information extraction, be of high efficiency, capable of wide bandwidth, have the stability and low noise needed for detection of small moving targets in the midst of large clutter echoes, be of high reliability and easy to maintain, and be of a size and weight suitable for its intended application.

Solid-state transmitters: There is currently much interest in solid-state radar transmitters. To some extent, such interest is understandable because of the extraordinary gains made in the past in the use of solid-state for receivers and especially for digital processing. Two advantages of a solid-state transmitter for radar are its ability to operate over a very wide bandwidth and its ease of maintenance. However, there are some serious limitations to the use of solid-state transmitters. An individual solid-state device, such as a transistor amplifier, is of low gain and low power so that many have to be combined to generate the required average power and high gain. Current solid-state devices have to operate with high duty cycles so they must employ long pulses that require the use of pulse compression. Long pulses also require the use of multiple waveforms with shorter pulse widths to cover the shorter ranges masked by the long pulse. There are no significant technical difficulties in using pulse compression and long pulses, or in using multiple waveforms; but they come with a price that is not found with power vacuum tubes. The result is that radars with solid-state transmitters are sometimes of larger size, lower efficiency, and higher cost than radars with comparable high-power vacuum-tube transmitters. Solid-state radar transmitters have interesting advantages, but they also carry some burden. It is not obvious that adequate research is now underway to find and develop new methods for reducing the limitations of solid-state

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transmitters or to find new types of RF power generators.

Power vacuum tubes: Solid-state devices have completely replaced vacuum tubes in receivers, signal processing, and data processing, but the vacuum tube is still the best way to obtain a high-power transmitter for the majority of radar applications. Power vacuum tubes can be made reliable and long life, as has been the experience with the original high-power BMEWS (Ballistic Missile Early Warning System) klystrons or satellite communications travelling-wave tubes. One reason there has been interest in solid-state devices is that some buyers of radars do not always make a complete evaluation of the various transmitter options, but require *a priori* that their transmitter be solid state. Some think this is because vacuum tubes have been with us a long while and are erroneously considered old-fashion technology. There have been some impressive advances made in power vacuum tubes. Military airborne fighter/attack radars employ light-weight, high average-power travelling-wave tube power amplifiers for their pulse Doppler radars. AWACS has recently replaced its conventional two-tube high-power klystron transmitter with a wide-bandwidth clustered-cavity klystron[15]. Actually, one clustered-cavity klystron could take the place of the two conventional klystrons, but two were installed for redundancy. Power vacuum-tube technology probably has not reached saturation[15,16].

It has been difficult to maintain interest in research and development of new RF power sources, but such efforts should be encouraged to continue and even expand. The transmitter is a significant part of a radar and it should not be thought that there is no value in searching for improvements and new concepts in radar power generation.

Information extraction

This has become more important as digital processing technology has improved. A properly designed radar can provide more information about targets than just their presence and location.

Target recognition: Radar can be designed to detect buried mines and to detect ballistic missiles, as well as to detect vehicles located in foliage. Although detection of these particular targets is possible, *recognition* of what is detected is much more difficult. In many cases reliable target recognition is not yet achievable. Detection of a radar output signal as a 'blob' on a radar screen is not always entirely useful if the type of target that produced the blob is not known. The distinctive wing-beat modulation of the echo from a bird in flight might allow one species to be recognised from another, but there are a very large number of bird species in the world. Radar meteorologists have searched for methods to recognise dangerous hail from less dangerous heavy rainfall, since heavy rainfall is not as serious a hazard to aircraft as is hail. ISAR (Inverse Synthetic Aperture Radar) can be used to recognise one ship class from another[17]. The modulation of the echo from a jet engine can allow the recognition of one class of aircraft from another[18]. Much progress has been made in the use of radar for target recognition, but there is need for more.

It is not likely that radar can ever provide the same type of target recognition capability as can optics (the human eyeball), but radar has the advantage of being able to operate at long range and under weather conditions when optics cannot function. It is not known whether the limits on radar information extraction have been reached; but target recognition, especially for military combat identification, seems important enough to continue to explore what else radar can do to provide the recognition of one class of target from another.

Image texture: Those involved with the remote sensing of the sea using airborne or spaceborne SAR (Synthetic Aperture Radar) have not been able to extract the type of information they might have wished (such as the sea conditions or the two dimensional sea spectrum). This is because a SAR does not image moving targets faithfully, and the sea is a target in motion. Although SAR images of the sea might look wave-like, microwave echoes from the sea are due to a collection of sea spikes, which are short duration (transient) echoes that come and go, seemingly sporadically. A radar image of the sea has a texture, even when observed with a SAR that distorts the image. One would think that the image texture ought to be related to its sea state or the wind conditions. It might be interesting to examine, therefore, the texture of a radar image to obtain a measure of sea conditions.

Phased-array antennas

An electronically steered phased array has been a popular antenna for some military radar applications. Radar antenna engineers have been clever enough to learn how to make the phased array work satisfactorily in applications, but the theory of the phased-array antenna does not seem to be complete and there is more that might be done.

Much of the theoretical analysis of phased arrays has been based on the infinite array. This model is used for convenience since a realistic finite array is more difficult to analyse than an infinite one. The mutual coupling between radiating elements in a finite array varies depending on the location of the element within the array. In an infinite array, all the elements see the same local environment so that the mutual coupling is uniform throughout the array, making analysis simpler. An infinite array is a strange creature, however. It has no far field, and it takes an infinite time to fill the antenna aperture or to steer the beam. Antenna designers are usually practical people. When faced with insufficient information they tend to 'cut and try' until something works. (This approach is not unusual in many fields of real-world engineering.) In spite of difficulties, however, one tries to strive for knowledge and understanding. It is not obvious that the infinite array model works as well as might be desired. The understanding of mutual coupling is far from complete[19]. The antenna designer usually concentrates on the effect that mutual coupling has on the element impedance, but there is more to mutual coupling. The finite size of the radiating element and any dielectrics or other passive materials in front of the aperture also influence the radiated pattern even if the element

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impedance is unaffected.

Another phased-array theoretical concept that might be questioned is when the antenna is steered to an angle where the element pattern has a null. Some antenna theorists will say that the energy delivered to the antenna by the transmitter will then be totally reflected back and the antenna voltage standing-wave ratio (VSWR) will be very large. It might also be questioned whether there really is such a thing as an 'ideal' element pattern (one with a cosine-shaped pattern).

There is no lack of successful phased arrays in practice. They have been achieved in spite of questions about the adequacy of the theoretical aspects of phased arrays. It has been some time since there was serious theoretical work on phased arrays. Computer techniques developed in the last ten to 15 years for the solution of Maxwell's equations have been very important for the calculation of radar cross-section and conventional antenna design. There might be some value in revisiting the theory of the phased array and applying the advances in the computer analysis of electromagnetic problems to the phased array. Since there is much interest in the application of the phased array as a radar antenna, its theory should be improved.

Endfire antennas[20]

The endfire antenna has not been used to any great extent in radar, even though it has been an excellent antenna for the US Navy's E2C Airborne Early Warning radar system. In that application it has decided advantages over a conventional planar phased array (mainly that it generates a vertical fan beam without the large drag of a vertical planar array). There are other applications where the advantages of an endfire antenna might be desired. They might be important in a shipboard air-surveillance radar when wind drag is a problem. In some applications it might be desired that the endfire antenna be steerable in elevation (as for electronic stabilisation on a pitching and rolling platform) and provide multiple beams as needed for monopulse angle-measurement or tracking.

Microwave sea clutter

The theory of radar echo from the sea based on Bragg scatter describes well the experimental observations made with HF and VHF radars. However, in the upper microwave region of the spectrum, especially at X band, Bragg theory does not apply and does not explain the experimental observations. A new theory of sea clutter is needed. It is known that in the microwave region the echo from the sea at low grazing angles is due to 'sea spikes'. These are discrete short-duration echoes that are somewhat randomly distributed in time over the sea surface. There is an important opportunity, and an important need, to understand the nature of microwave sea clutter based on knowledge that sea spikes are the dominant, if not the only, factor that is the source of the radar sea echo at the higher radar frequencies.

6 Some less interesting radar concepts

There have always been radar concepts that are less exciting than might be expected from the wide attention they receive or from the claims of their press releases. The following is a brief list of some of the technologies and concepts that might be approached with caution. It should be noted, however, that not all will agree with everything mentioned below, nor should it be expected that everything listed will never be of importance in the future. There are too many examples from the past where things that seemed to have limited merit eventually became of importance because of the appearance of a new needed application and/or the appearance of new technology. Thus the following list is always subject to revision at any time.

Superresolution: The desire to achieve resolution in angle better than predicted by 'theory' has appeared and reappeared more than once ever since the early days of supergain antennas. Although the writer is not aware of a completely satisfactory 'theory' of resolution, most of the 'superresolution' methods proposed in the past have failed because (1) they were based on mathematical models that did not always follow from Maxwell's equations (supergain or superdirectivity are examples), or (2) they utilised nonlinear mathematical operations that do not work with coherent signals (which is what radar echoes from the same transmitter are), or (3) they failed to recognise that resolution depends on the signal-to-noise ratio (resolution is easier to obtain with high signal-to-noise ratios).

Bistatic radar: The first radars in the 1930s were bistatic (widely separated receiver and transmitter), but radar didn't become a practical reality until the transmitter and receiver were co-located (monostatic). There might be one or two limited applications where bistatic radar might be equal to or better than the equivalent monostatic radar, but for the vast majority of applications a monostatic system is almost always the better choice. Multistatic radars (those with more than two sites) are even less attractive.

Non-cooperative transmitters with bistatic radar, also called non-cooperative bistatic radar or passive coherent location: This is a bistatic radar where the transmitter belongs to someone else. It might utilise a commercial TV or FM transmitter or a transmitter belonging to a monostatic radar that can supply the desired coverage. In addition to all the limitations of any bistatic radar, in a non-cooperative bistatic system there is no control over the system coverage, waveform, spectrum, purity, or stability of the transmitted signal—including even whether the transmitter will be operating when it is needed.

Remote sensing of the environment: Other than the high-precision altimeter for measuring the geoid, it seems that radar for remote sensing of the environment from space has not achieved the performance promised by its proponents. The remote-sensing application that has been the exception is the highly successful use of ground-based radar for weather observation; but radar meteorologists seldom think of themselves as being a

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part of the remote-sensing community.

CFAR (Constant False-Alarm Rate) receiver: It is sometimes forgotten that CFAR was originally employed in radar as a 'crutch'. It was necessary because the early radars that employed automatic tracking were of limited capability and became overloaded with only a modest number of targets, clutter 'breakthroughs', jamming, or interference. CFAR basically turns the gain down to keep such nuisance echoes from entering and overloading the tracker. The reduction in probability of detection produced by CFAR, suppression of nearby target echoes, degraded range resolution, loss in signal-to-noise ratio, and false echoes in patchy clutter are all tolerated in order to prevent the tracker from being overloaded. The goal should not be to continually 'improve' CFAR but to eliminate the need for it altogether by designing good radars that eliminate clutter and suppress jamming. Eventually (if not already), digital processing should be capable of allowing the tracker to eliminate the nuisance echoes itself without being overloaded.

Fully polarimetric radar: It can be of benefit in certain applications to employ radars that operate with two orthogonal polarisations (such as horizontal and vertical polarisation). A 'fully polarimetric' radar is one that provides, in addition to amplitude, the phase relations amongst the two co- and two cross-polarisations. It is always desirable to have as much information as available (and affordable) from a radar, but at present there have been few, if any, applications where a fully polarimetric radar (one that obtains the complete polarisation matrix) provides information that is critical for some needed application. Thus dual polarisation might be useful in some applications, but a fully polarimetric radar does not seem to have significant added capability to justify its use in most applications.

Ultrawideband (UWB) radar: A highly useful example of a UWB radar is the ground-penetrating radar designed to detect buried underground objects. Almost all of the other potential applications described by proponents of UWB radar might have less merit than sometimes claimed.

Other areas still awaiting demonstrations of real promise are *optical processing* (it gets better with time, but digital processing gets even better); *optical phased-array radar*, which has some limited interest for transmitting arrays but not for receiving arrays; *noise radar*, one that utilises a random noise waveform (its claimed benefits are obtained better and more easily with pulse compression radar); and *delta-K radar* and its cousin the *two-frequency MTI*, which use two separated frequencies and process the echo signals to obtain their difference frequency (in a nonlinear operation), for which the claim is that the radar has the properties of a radar at the difference frequency rather than the RF frequency (which it does not). The *high-power CW (or FM-CW) radar* goes back to the early days of radar and was the basis for the successful HAWK air-defence system, but CW has now been replaced almost entirely in high-power applications by pulse Doppler radars.

Ten years ago a list like that given above would likely have included millimetre wave radar and the gyrotron. Things have changed, however. As mentioned previously in this paper, the high-power gyroklystron amplifier has been made practical for radar application. There are also applications that didn't exist in the past for which millimetre wave radar seems to be better suited than microwave radar. Thus the above listing should not be considered to be chiselled in stone. It could change as circumstances change.

7 Concluding comments

As was mentioned at the beginning of this paper, one cannot accurately predict the future of a technology beyond the next several years. If, 30 to 40 years from now, future radar engineers were to look back on their history, it might very well be that only a few, if any, of the 'opportunities' mentioned in this paper ever have come to fruition. If experience is any guide, what will be the major new efforts in radar in the future—just as in the past—will likely have come as unexpected surprises not obvious at present.

The following summarises the 'messages' that might be obtained from this paper:

- Although there have been many factors since the 1930s that have influenced the development of radar, the major advances that have been highly significant might be: (*a*) the maturing of the heavy bomber aircraft in the early 1930s that led to the need for radar for air defence and its independent and almost simultaneous development in eight countries prior to the start of WWII; (*b*) the invention in 1940 of the high-power microwave cavity magnetron; (*c*) the appearance in the 1950s of the high-power klystron amplifier; (*d*) the use of the Doppler frequency shift to separate moving targets from large clutter echoes; (*e*) digital signal processing technology that has been the basis for many of the significant advances in radar ever since the 1970s.
- Most of the current military radar systems were conceived in the 1960s and eventually will need to be replaced by new radar architectures rather than continual upgrades.
- HF over-the-horizon radars can be more fully utilised. Better system architecture is now available for enhanced capability.
- Weather radars experienced an almost complete 'make-over' in the 1990s and further improvements can be expected.
- The simple elevated rotating planar mirror reflector in a small aerostat illuminated by a conventional pencil-beam radar from the ground or ship is a relatively inexpensive way to extend the radar horizon against low-altitude missiles out to ranges of almost 60 nmi.
- An air-surveillance radar operating over a wide range of frequencies, as did the experimental radar known as Senrad, can significantly reduce vulnerability to electronic countermeasures, provide improved automatic tracking because of its relatively uniform coverage in elevation, obtain target height based on measuring the time delay between multipath echo signals (using only a fan-beam antenna), obtain approximate recognition of the general type of aircraft target, and employ the radar transmission itself to communicate between nearby

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radars defending the same region.

- A future ubiquitous radar employing digital beam forming (DBF) and digital signal processing that looks everywhere all the time can perform multiple radar functions simultaneously rather than sequentially. A good initial candidate for development as a DBF radar is the HF over-the-horizon radar.
- When a DBF radar operates as an ubiquitous radar with high-duty-cycle waveforms and with multiple frequencies it can provide much lower probability of intercept (LPI) than conventional LPI radar concepts.
- High-power RF sources at millimetre wavelengths, as well as potential applications better performed at millimetre waves than at microwaves, now make these frequencies more attractive than in the past.
- Advances in digital technology are likely to continue to be a major driver in the advancement of radar in the near future, just as they have been in the past.
- It should not be assumed that there are no further opportunities for advances in RF power sources. Serious investigations of this vital technology should be encouraged.
- Information extraction that has lead to methods for target recognition has been a valued addition to radar capabilities and should continue. The extraction of information available from the texture of a radar image of the sea is an example of something that might be explored.
- Further research leading to the better understanding of phased-array antennas should be pursued.
- Endfire antennas have seen only little (but important) application in radar, but they might be able to do more.
- There needs to be a new theory of microwave sea echo based on 'sea spikes'.
- Several radar concepts that appear in the technical literature, the trade press, and in press releases might be less important at present than indicated by the frequency of their appearance. It is not that they will never have any useful applications, but they should be approached with caution.
- This paper has provided a limited view of what could be done in radar in the future. It does not claim to include everything that might be of potential value in the search for improved radars.

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First received 23rd May and in final form 29th August 2002

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