WHITHER RADAR?

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This paper demonstrates that radar has a future and seeks to determine the direction of radar evolution. The constraints imposed by requirements, technology, cost and fashion are explored in turn. The paper concludes that the principal future trend will be towards higher resolution in space and Doppler velocity, made possible by advances in processing technology.

1. INTRODUCTION

The evolution of radar, like that of many other branches of engineering, is determined by four constraints: requirements, technology, cost and fashion. Having first discussed these constraints and their role in determining past and present trends, this paper will attempt to extrapolate the constraints to predict the future.

First of all, however, a fundamental question must be answered. Has radar any future at all?

From prehistoric times, military science has progressed by a series of inventions. Some, like the crossbow, artillery, the torpedo and the cruise missile give an advantage to the attacker. They are basically destabilizing weapons, although it may be necessary to procure them for defensive and deterrent purposes. Other inventions such as the stone castle, armour and radar favour the defender. They are basically stabilizing influences, although they may also be used to support attacks. To make a country safer from surprise attack a radar umbrella is a first requisite.

Apart from its military purpose, radar is a necessary part of the system which maintains the safety of travel by air or sea. Other cooperative means of control may bear much of the routine burden of ensuring safety, but there remains a need for primary radar to cope with the emergencies.

It may therefore be confidently assumed that radar has a future in both military and civil roles. Since the military requirements are more demanding, they usually provide the main impetus for evolution.

2. REQUIREMENTS

The three principal performance requirements for a radar sensor are sensitivity, resolution, and data rate.

Sensitivity is concerned with the detection of targets of limited echoing area at given ranges. A major air defence radar may be required to detect small aircraft or missiles at ranges of several hundred kilometres. At shorter ranges, the targets of interest may be as small as mortar bombs for weapon locator radars or periscopes for anti-submarine radars. The civil air traffic control radar must detect gliders and ultra-light aircraft if they stray into controlled airspace.

Resolution is concerned with the separation of targets from clutter and from each other. The accuracy with which the target position can be determined depends upon the resolution performance. Resolution may be in any or all of four dimensions: range, azimuth bearing, elevation and Doppler velocity. Clutter may be due to reflections from land, from sea, from weather or from hostile chaff.

Data rate is important as it concerns both the rapidity with which a target may be first detected on entering the radar coverage and also the accuracy with which it can subsequently be tracked. In traditional rotating radars, search data rates and tracking data rates are identical and equal to rotation rate. In new adaptive radars, search and tracking rates may be variable according to need.

A further important requirement for a military radar is survivability. Survivability may be physical or functional. Physical survivability is concerned with counters to direct physical attack and involves techniques such as concealment, mobility and hardening. Functional survivability is concerned with matters such as resistance to hostile jamming and detection of 'stealth' targets.

The ability of the radar sensor to operate in difficult natural environments is also important but is not an evolutionary factor. The natural environment is permanent.

The radar system must be able to handle the data gathered by the sensor. The data must be processed into a convenient format, possibly blended with data from other sources and finally presented to the user. The user may be a manual control centre, a fully automated network or something between the two.

The requirements of sensitivity, resolution and data rate may be quantified using the formulae derived in the Appendix.

From the Appendix, equation (A6), the signal/noise ratio of the radar is given by:

$$\frac{PA\,\sigma T\eta}{4\,\pi R^4\,\Omega\,NK} \qquad (1)$$

Now the target echoing area σ, the range R and the coverage Ω are determined by the operational requirement. The search interval T cannot exceed some value determined by the operational requirement. The limiting factor may be either initial detection delay or track update rate.

The efficiency η and the noise factor N are limited by technology and by certain design compromises. The constants π and K are fixed. Only the mean power P and the antenna aperture A are available to the sensor designer as free variables.

To ensure an adequate detection performance, the signal/noise ratio must attain some minimum value depending upon the detection probability and false alarm rate specified and upon the target fading statistics. A typical signal/noise ratio requirement is around 15 dB. The threshold is set some 7–8 dB above mean noise level to ensure a low false alarm rate and the mean signal level must be 7–8 dB above threshold to ensure a high detection probability. This requirement determines a minimum acceptable value for the product PAT.

In practice, it is easier to detect targets with a long search interval and a high signal/noise ratio than with a larger number of inspections at a lower signal/noise ratio. The search interval *T* should approach the maximum tolerable value. The formula will then determine a minimum value for the power-aperture product *PA*.

The formula does not contain frequency explicitly, but a number of parameters are frequency dependent. For example, echoing area varies with frequency according to target size, shape and stealth treatment if any. Efficiency is frequency dependent, losses generally rising with radar frequency. Receiver noise factor also increases with frequency. Apart from the higher efficiencies obtainable at lower frequencies, the ambiguity problems are eased.

The unambiguous range of a pulse radar is given by

$$\frac{c}{2f} \tag{2}$$

where f is the pulse repetition frequency (p.r.f.) and c the velocity of light. For any given unambiguous range, this formula determines the highest p.r.f. which can be used, regardless of radar frequency.

The radar will have ambiguities in the Doppler radial velocity dimension with repetition at a velocity interval V, sometimes called the blind velocity spacing. This velocity is given by

$$V = \lambda f/2 \tag{3}$$

where λ is the wavelength in free space.

For a typical medium range (150 km) radar, the maximum p.r.f. is 1000 Hz, neglecting some practical matters such as pulse duration and transmitter/receiver switching time. The corresponding blind velocity spacing V is 115 m/s at L-band, 23 cm wavelength, but only 15 m/s at X-band, 3 cm wavelength.

If the clutter rejection notch in the filter bank is wide enough to reject rain clutter, typically 1 to 4 m/s wide, there will be little difficulty in eliminating the blind velocities at the longer wavelengths by using a second lower value of the p.r.f. for alternate inspections. At the shorter wavelengths, turbulent rain may leave little space for target detection between the clutter rejection notch and its ambiguities.

Consider now the question of resolution. The number of resolution cells available is limited by the bandwidth of the receiver B as shown in the Appendix, equation (A11). This formula is also independent of radar frequency, but the shape of the resolution cells is strongly frequency-dependent.

With antenna apertures of operationally acceptable dimensions, a low radar frequency will yield a wide azimuth and elevation beam. For a given search interval T, the dwell time will be long, permitting much narrower cells in the Doppler dimension. For a given bandwidth B, the range cell width will be fixed. If the bandwidth is 1 MHz, the pulse duration will be 1 μsec and the range cell 150 metres. For a typical antenna aperture of 5 metres at L-band, the beam will be 3.22° wide giving an azimuth cell of 5600 metres at 100 km. At X-band the same aperture would give a beam only 0.42° wide with an azimuth cell of 730 metres at 100 km. Now for a radar wavelength of 3 cm, a 5 metre aperture is very large and a bandwidth of 1 MHz is comparatively modest. Even so, the cell is highly rectangular. For accuracy of tracking, it is preferable to make the cell more nearly square, but this is an ideal seldom approached in practice. It does however provide an argument in favour of the higher radar frequencies.

The use of higher frequencies to narrow the antenna beam is also desirable in the presence of jamming, since jamming in the antenna beam is far more difficult to combat than jamming in the sidelobes, which may be some 30 to 60 dB lower.

In practical radar systems, clutter can often only be defeated by use of the Doppler dimension. This sets a minimum value for dwell time t and thus produces a conflict between the requirements for narrow beams and short search intervals, equation (A4). This conflict can be resolved by using a multiple beam receiving system. If the number of beams is m, then

$$t = T\theta\phi m/\Omega. \tag{4}$$

The number of resolution cells inspected per second and the total receiver bandwidth are both increased by the factor m, since m parallel receiver channels are now required.

The transmitting antenna gain must be reduced by m to ensure that m beam positions are simultaneously illuminated. Since dwell time can be increased by m for the same search interval, the PA product required for a given detection sensitivity is unchanged.

The theory given above is deliberately highly simplified in order to bring out as clearly as possible the fundamental relationships between the major radar parameters. For accurate performance prediction, one of the standard text-books should be used, taking into account all the various secondary effects and design compromises.

3. TECHNOLOGY

Four broad categories of technology are involved in radar design. These are antenna, transmitter, receiver/processor and data handling/radar management technology.

At the birth of radar some fifty years ago, antenna technology was perhaps the best established. Electronic beam steering was already known in HF communications and both the electrical and the mechanical design of high gain arrays were well understood. The CH antennas used for air defence radar during the 1939–45 war used triple 110 metre towers. The background experience available from physical optics and from limited experiments with microwaves was adequate for the needs of first generation equipments in the upper frequency bands.

After the war, antenna technology progressed swiftly. By the twenty-fifth birthday of radar, a wide variety of different classes of antenna had been analysed theoretically and demonstrated experimentally, including several classes with electronic scanning. Few of these advanced ideas were exploited in practical systems as they were not essential to meet the current requirements. Furthermore, the data management systems needed for their effective use were not available.

The second twenty-five years has seen a slowing down in antenna technological growth. There has however been a revolution in design techniques due to the use of computer aided design, manufacture and testing (CADMAT). Current antenna technology remains more than equal to the requirements of the shorter term future, and will continue to be so in the longer term with reasonable further investment. Antenna technology is not therefore a significant constraint in the radar evolutionary process.

By contrast, the generation of high power radar waveforms has been a significant constraint. Early radars operated in the VHF bands to take advantage of available broadcasting and television technology. High peak pulse powers did not become available until the magnetron was invented. The later inventions of the travelling wave tube and the crossed field amplifier enabled fully coherent radar transmitters to be designed, more recent tubes having grid control and frequency agility capability. Nevertheless vacuum tubes have always been critical path items in the development of new radars and one of the principal sources of serious faults in operation. Output tube failure is usually total system failure.

Recently, the solid state amplifier has started to take over. Currently, solid state transmission is established at 23 cm wavelength and will soon be so at 10 cm. Extension to 5 cm, 3 cm and 2 cm bands may be expected to follow during the remainder of this century. Solid state transmitters use a large number of separate amplifiers, usually feeding separate antenna elements, thus the failure of one unit has only a slight effect on the overall radar performance.

Receiving and signal processing technology has always been and is likely to remain a major constraint in radar evolution. While low noise amplification at the lower end of the frequency band was familiar from communications experience, low noise reception of microwave frequencies had to be developed for radar. Early equipments often had simple crystal diode mixers at the receiver front end. Current equipments use low noise solid state amplifiers or sophisticated balanced mixers with several pairs of diodes.

The cancellation of clutter has proved a major problem in the past. Early radars used glass delay lines to enable a return pulse to be stored for one pulse interval and subtracted from the next return. Fixed clutter was then cancelled while targets, having moved slightly between pulses, were not. If targets moved radially through an integral number of half wavelengths between pulses they appeared to be fixed and so were cancelled with the clutter. This is the blind velocity problem of equation (3). Improved velocity response characteristics were obtained by double and triple cancellation and by the application of feedback, but delay-line cancellation remained a rather inflexible technique.

The cancellation of clutter was greatly improved by the use of coherent transmitted waveforms with range-gate Doppler filter bank receiver processors. Radars were developed in the early nineteen-seventies using these techniques to obtain clutter reductions of order 70 dB using advanced analogue filters.

The availability of fast digital processing revolutionised radar reception. Much better resolution in range and velocity became economically possible and the choice of repetition frequency became much more flexible. The limiting factors became the analogue/digital converter and the sheer capacity of the subsequent processor.

Analogue/digital converters remain a constraint, it being difficult to combine high sampling speeds with wide dynamic range. High sampling speeds are needed for fine range resolution and wide dynamic range to avoid limiting on clutter and other large signal returns.

The capacity of the subsequent processing is a cost rather than a technology limitation as a number of processors may be connected in parallel, interlaced in time, to increase the total capacity. Current advances in very high performance integrated circuits (VHPIC) will ensure a steady increase in available processing power in future years.

In early radars, radar management was hardly a problem. Data was displayed on long-persistence cathode ray tubes and interpreted manually. The inflexible characteristics of the radar gave little scope for real-time control.

Over the years, more and more radar parameters have become variable and capable of software control. Currently antenna beam position, transmitter frequency, pulse characteristics and repetition rate, signal processing characteristics, threshold settings and tracking algorithms have all become controllable.

The optimum control of all these facilities requires a large and complicated software package. Decisions have to be taken far faster than manual control would permit. Currently it is the 'thinking' time of the management computer rather than the speed of response of the various controllable elements which sets the limit on radar adaptivity. The future availability of better software languages and faster processors should produce a steady improvement in radar management capability.

Note the importance of making the software comprehensive enough to make a near-optimum response to any possible situation. Note also the difficulty of testing this capability.

4. COST

During the first years of radar, the importance of air defence meant that cost was not a serious limitation. Even during the nineteen-fifties and sixties, single nations still indulged in the luxury of developing two or more rival equipments to solve a single problem. During the later years and in the future, cost has become and will continue to be a major evolutionary constraint.

Development costs can be reduced in proportion to total procurement or life cycle costs by increasing production numbers. This may be done, for example, by using common equipments or sub-assemblies for more than one requirement. The agreement of common international requirements permits multinational development, affording real savings if the requirements are truly common and the number of participants not too large. From two to four is perhaps ideal. With large numbers of participants the costs of management, translation, interfacing and other development overheads become increasingly significant.

It is interesting to consider the effect of cost-effectiveness optimisation on the choice of radar parameters.

Consider first the simple radar in which the most expensive items are the antenna and transmitter. Antenna cost is approximately proportional to aperture area A (equation (1)) and transmitter cost approximately to mean power output P. For a given total cost for both units the PA product is maximized when the costs of the two are equal.

Investigation of radar designs of the nineteen sixties suggests that this rule does lead to a balanced and cost-effective system. More recently the trend towards planar arrays of higher performance has increased the cost per unit area to a greater extent than the inflationary increase in transmitter cost, thus there is a trend towards smaller apertures and higher mean powers. The same trend has been encouraged by the preference for all future military radars to be transportable or mobile.

Whereas for traditional radars with high power tube transmitters and reflector antennas, there was little difference between the costs of 23 cm and 10 cm radars of similar performance, the same may not be true in the future. For a given aperture size, a 10 cm radar will have 2.3 times the number of linear array elements as a 23 cm radar, or 5.3 times the number of point source elements. The 10 cm elements will be cheaper than 23 cm elements, but not by so much as the above ratios. In consequence, the 10 cm antenna will be significantly more expensive per unit area than the 23 cm antenna.

This again affects the optimum PA balance. For high power tube transmitter radars, a 10 cm system will tend to have a more powerful transmitter and a smaller aperture than a comparable 23 cm system. This is well illustrated by comparing the Marconi S713, 65 sq. m and 10 kW, with the Plessey/Gilfillan AR320, 22 sq. m and 25 kW approximately.

Looking ahead to the wider adoption of solid state transmitters feeding separate antenna elements, the P/A optimization rule suggests that if the element P/A ratio is correct, any size of radar built up from these elements will have the same P/A ratio and will also be correctly optimized.

It could be dangerous to design radars solely by such cost optimization rules as they do not take account of the benefits of using cheaper but not-quite-optimum power transistors or the operational advantages of a not-quite-optimum beamwidth, to give two examples. The optimum is comparatively broad, thus making the P/A cost ratio 2 instead of unity increases the predicted cost by only 6%. However, if a projected design leads to a P/A cost ratio wildly different from unity, it is worth checking to see if there is a cheaper solution.

The costs of digital processors and stores have fallen dramatically over the last few years. This trend may be expected to continue, making it possible to include more autonomy in the radar without disproportionate cost increase. While the costs of digital hardware fall, software remains expensive. The use of advanced programming languages, modular programs and correct computer architecture will help to contain software costs but the best method of cost reduction is to spread the one-off software development costs over the largest possible production run of equipments. Note the high cost of testing complex software.

5. FASHION

The concept of fashion may seem out of place in a serious discussion of radar. Nevertheless, there are similarities between the fashion trade and radar marketing. If there are two equally meritorious solutions to a requirement, one widely purchased and the other comparatively unknown, it requires a brave customer to purchase the first example of the second solution. Procurement authorities without a strong technical support establishment tend wherever possible to choose designs which have already been endorsed by other customers.

There is also a strong preference for evolutionary improvement rather than revolutionary change amongst those staffs concerned with operation, maintainance, training and general logistic support. There are good practical and financial reasons for this attitude and their importance should not be lightly dismissed.

Thirdly, there is often a desire on the part of customers to keep up with the neighbours for prestige rather than sound technical reasons, thus specifying a more powerful system than is really necessary at the time. Such customers are at least better equipped to face the future than the ultra-conservative administrations that are content to buy the ultimate update of an obsolescent concept.

Such attitudes undoubtedly sway the trends of radar system evolution by making it more difficult to market any really innovative sensor. It is difficult to reduce fashion to analytical terms, but it must still be taken into account in predicting the future.

6. THE FUTURE

Having set out a framework of constraints that determine the course of radar evolution, the future trends can now be considered.

Consider first the future trend of sensitivity. Future military radars will be required to detect smaller targets in more difficult environments, hence better sensitivity. At the same time, the constraints of survivability and cost will oppose any significant growth in antenna aperture size. The trend may in fact be towards slightly smaller but more sophisticated antennas. The use of solid state distributed transmitters integrated into the antenna structure reduces losses and so increases effective radiated power. In mean power capability, a gradual increase may be expected. This will offset the slight decrease in antenna size.

Microwave radar coverage is limited by earth curvature, thus there is little to be gained by extending maximum range beyond about 400 km. Beyond this, only very high altitude targets can be detected. To cope with low altitude threats larger numbers of shorter range radars provide a better solution. There is thus no real need to increase maximum range, indeed, a small reduction may be operationally acceptable in exchange for lower cost, better sensitivity or higher mobility.

If little real increase in overall *PA* product can be expected, where then can improved performance be found? The answer is in the other fundamental requirements, resolution and data rate.

As shown in equation (A11), the number of resolution cells inspected per second is constrained by the overall signal processing bandwidth. A radar of twenty-five years ago might have had a single receiving channel with a bandwidth of a fraction of a megahertz. A modern radar such as Martello has eight receiving channels, each of five megahertz bandwidth, total forty megahertz. Now the transmitter and antenna technology required for this class of radar has been available for many years in a less elegant form but the processing power required to assimilate the torrent of information has not been economically available. The transmitter and antenna technology of today is able to generate information at rates at least an order of magnitude greater still and will probably do so when sufficient processing capacity is available to exploit it. Here then is a major future trend.

The practical use of this future capability can take many forms, but perhaps the most important will be in multiple beam reception. As shown in equation (4), multiple beam technology provides increased resolution without loss of sensitivity and without making individual resolution cells excessively rectangular. The same total bandwidth may cover a single wide beam with a small range cell or a number of narrower beams with proportionally larger range cells, the latter being much nearer to the ideal square tracking cell.

A further use for multiple beam reception is in multistatic radar in which some sites have only pass-

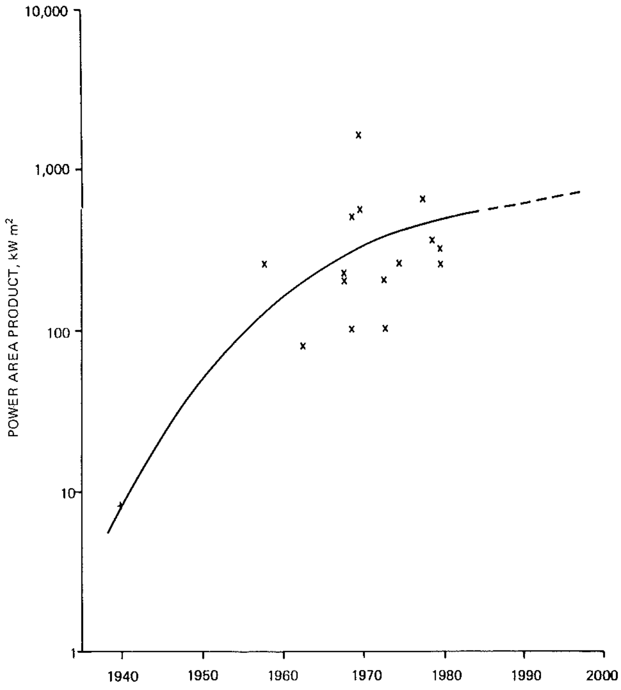

Fig. 1. The growth of the power-area product with time

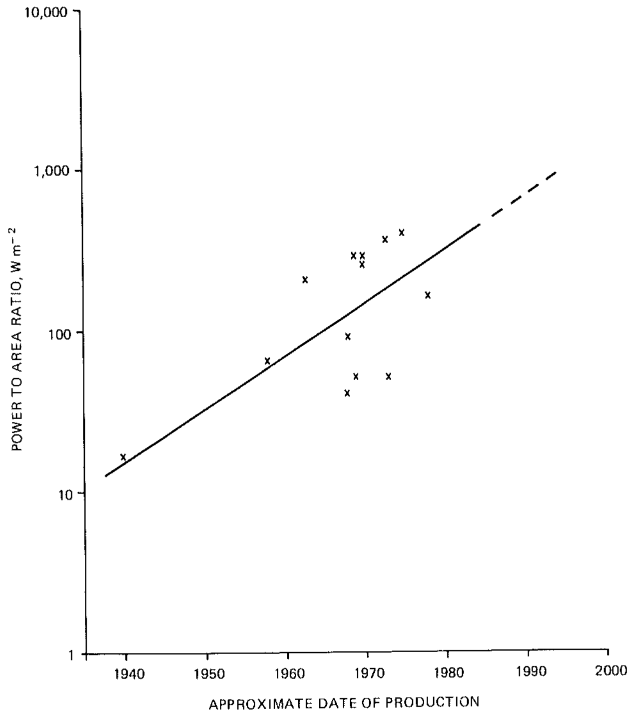

Fig. 2. The growth of the power to area ratio with time

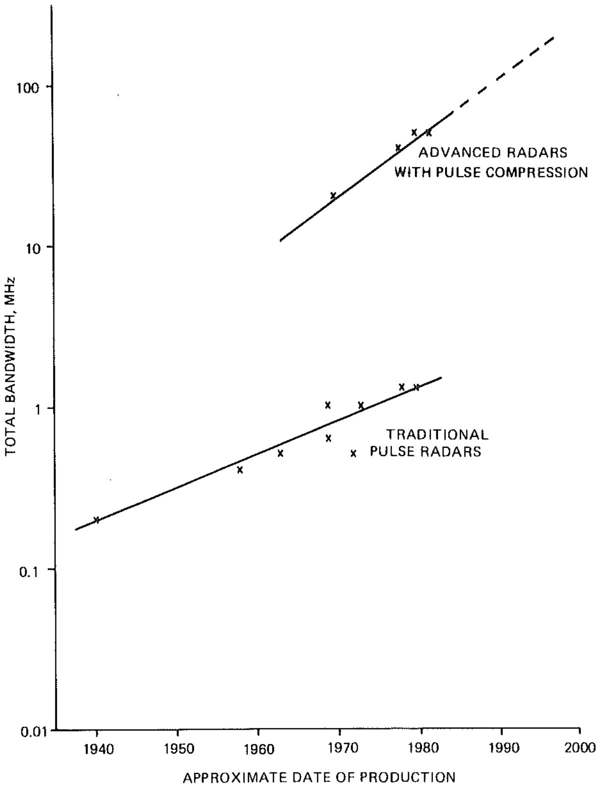

Fig. 3. The growth of total system bandwidth with time

ive equipments. This provides a substantial improvement in overall survivability by enabling some sites to be physically and electronically concealed. It may be expected that the major air defence sensor networks of today will in due course evolve into the active and passive multistatic networks of tomorrow.

The remaining major trend will be towards greater use of adaptivity. All major radar parameters are now software-controllable and increasing use will be made of this capability as military environments and threats become more severe, creating a need, and as computers become more intelligent, providing a means.

It may be helpful to consider some practical examples. The use of adaptive antenna scanning enables different parts of the coverage to be searched at different rates. The low elevation sector, where surprise attack is most likely, can be searched most frequently. When a target is discovered its existence can be quickly confirmed, its ambiguities resolved and its precise four-dimensional position established. A few further inspections in rapid succession can initiate a track and provide an assessment of the target to the control centre. Afterwards, tracking update rates may be adjusted according to target classification and behaviour. This represents a far more efficient use of energy than the traditional rotating fixed-beam radar whose rotation rate is a compromise between many conflicting requirements.

The use of adaptive frequency agility provides a counter to jamming, also a means of decorrelating fading, multipath and some classes of clutter.

The use of adaptive waveforms enables more efficient use of energy by reserving long pulses for difficult long range inspections. At shorter ranges or for less demanding tasks shorter pulses or lower peak powers may be sufficient. Adaptive coding of pulses provides pulse compression and, together with adaptive waveforms, additional protection against countermeasures. Adaptive control of pulse repetition rate optimizes the waveform for various tasks and for various environments.

Adaptive Doppler filtering, using clutter maps to control adaptive thresholds, optimizes detection performance in irregular clutter environments. Adaptive tracking algorithms adapt themselves to different kinds of target behaviour.

The optimum use of all this potential adaptivity, as explained in the technology chapter, requires advanced software operating at higher speeds than are currently available. Future growth in information technology will in due course meet this need.

What of the remaining constraints, cost and fashion? It has been argued that falling costs of digital processing will permit a gradual growth in this area, allowing the predicted improvements in resolution, data rate and adaptivity to take place. However, fashion will ensure that the changes occur in an evolutionary rather than a revolutionary way, and that the time scale of evolution will always be a little slower than purely engineering considerations would permit.

APPENDIX

Consider a simple radar of mean power P and antenna gain G. The power intercepted by a target of echoing area σ at range R is given by:

$$PG\sigma/4\pi R^2 \qquad \text{(A1)}$$

If this power is reradiated isotropically, the power intercepted by the radar antenna of area A is given by:

$$PG\,\sigma A/(4\pi R^2)^2 \qquad \text{(A2)}$$

If the target is illuminated for a dwell time t and if all the returned signal is coherently integrated, the noise power in the receiver is given by the final bandwidth, $1/t$, multiplied by the receiver noise factor N, multiplied by the product K of Boltzmann's constant and the absolute temperature:

$$NK/t \qquad \text{(A3)}$$

If the radar is required to search a coverage solid angle Ω in a total time T and if the radar beamwidth is θ in azimuth and ϕ in elevation, then:

$$t = T\theta\phi/\Omega \qquad \text{(A4)}$$

The gain of the antenna is related to the beamwidth by the formula:

$$G = 4\pi/\theta\phi \qquad \text{(A5)}$$

Putting together equations (A2), (A3), (A4), (A5) and including an efficiency factor η which represents all the losses in the radar, the signal/noise ratio is given by:

$$\frac{PA\,\sigma\,T\eta}{4\pi R^4\,\Omega\,NK} \qquad \text{(A6)}$$

Note that frequency does not appear explicitly in this formula although several of the parameters are frequency dependent.

Consider now the number of resolution cells in the radar coverage. The number of angular cells is given by:

$$\Omega/\theta\phi \qquad \text{(A7)}$$

If the radar is a simple pulse radar of pulse duration τ pulse repetition frequency f, then the number of unambiguous range cells cannot exceed

$$1/f\tau \qquad \text{(A8)}$$

The number of Doppler filter channels cannot exceed the number of pulses in the dwell time. This number is

$$ft \qquad \text{(A9)}$$

Combining (A7), (A8), (A9) and using (A4) to eliminate t, the total number of resolution cells in the four dimensions cannot exceed n where

$$n = T/\tau \qquad \text{(A10)}$$

Now $1/\tau$ is the bandwidth B of the receiver and n/T is the maximum number of resolution cells which can be inspected per second. Thus

$$n/T = B \qquad \text{(A11)}$$

In practice, the number of range cells will be less than in the ideal case considered above because of the receiver blanking during transmission. The bandwidth B will be greater than the reciprocal of the pulse duration. Because of the need for clutter cancellation, the number of useful filter channels may be less than the number of pulses integrated. In a typical practical radar, the number of useful resolution cells may be only about 30% of the maximum value derived above.