

# Low probability of intercept radar strategies

A.G. Stove, A.L. Hume and C.J. Baker

**Abstract:** To reduce probability of intercept, in most cases, the form and magnitude of the radar transmissions are designed to spread energy over as wide a range of dimensions as possible. Equally, in response to this, designs for electronic surveillance measures (ESM) systems have been postulated that increase receiver sensitivity. Their purpose is to increase detection range beyond that of the radar (or to an adequate range if they are to be forward deployed). The authors examine the evolving nature of the relationship between advanced 'low probability of intercept' (LPI) radar designs and future trends in ESM receiving capability. This relationship is far from straightforward, being both probabilistic and dependent on environmental and operational factors. Indeed this is complicated still further by the issue of affordability. The authors compute the performance of ESM and radar systems for a number of cases, including not just simple interception, but also the extraction of information from intercepted signals. In this way the key factors influencing the detectability of LPI radar systems are determined. It is demonstrated that it is never possible to be completely certain that a radar system has not been detected and that the most appropriate way to implement an LPI radar design is always closely related to the tactical environment in which the radar system will be used. Indeed this often overrides the technical aspects of system performance.

## 1 Introduction

Monostatic microwave radar systems using active emitters have a number of inherent advantages. They provide the ability to operate in bad weather and cover wide areas rapidly. If radar emissions can be routinely detected and jammed, then their effectiveness as an all weather, wide area sensor is compromised. It is quite possible in the battlefield of the future that radar systems that do not exhibit good low probability of intercept (LPI) characteristics will be of little use. As an alternative, operation at frequencies other than microwave could be employed but this may result in non-optimum combinations of resolution and detection range. However, it must be recognised that as active sensors, traditional radar systems will always have a finite probability of intercept. A further alternative is to use a bistatic approach that has the advantage of effective passivity but the disadvantage of system complexity. Bistatic operation using transmitters of opportunity results in a loss of control over system performance that may be unacceptable.

Thus, the analysis of the present and future LPI capabilities of radars, and of systems designed to intercept them, is of importance and provides a baseline against which the performance of other approaches can be compared. Many of the techniques designed to lower the probability of intercept of a radar system are well

documented [1–3]. Techniques which can be used to make it more difficult to intercept and exploit the transmissions include using high duty cycle waveforms to spread the transmitted energy in time, using wideband waveforms to spread it in frequency and using wide transmitter beams to spread it in space. In this paper we analyse the effect of using these techniques and consider whether there are any fundamental limits to the ability to detect radar emissions. The minimum emission levels from future monostatic LPI radar systems are computed and compared to other RF sources likely to be found on the future battlefield. The paper provides an analysis of the likelihood of intercept of a 'baseline' LPI radar, based on currently available technology, which will then be used to explore future directions in which the radar and the intercept receiver may develop. We highlight the distinction between the interception and the exploitation of signals, in particular the way that the latter requires an ability to distinguish some of the characteristics of the signal other than just its existence.

The potential appearance of bistatic radars using emitters of opportunity is another form of exploitation of radar transmissions. The paper examines the effectiveness of LPI techniques in preventing this exploitation and also considers the need for robust LPI designs to defend against attempts at exploitation which cannot be envisaged in detail when the radar is designed.

The paper examines a typical scenario for the balance of detection range between a radar system and an intercept receiver with the latter having the performance of a typical high quality in-service ESM system. This establishes a baseline from which other scenarios can be considered, particularly improved sensitivity of the intercept receiver and what the radar designer can do to counter this. This includes derivation of the concept of the 'matched incoherent receiver,' which overcomes the mismatch currently found between the bandwidths of radars and intercept receivers. The LPI performance that can then be obtained is discussed, together with its effects on the ability to use the radar for its intended purpose.

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As a final remark in this introductory Section, we note that care must be taken in making use of experimental measurements of the detectability of current LPI radars. This is because detection of low-peak-power, long duty cycle, waveforms has not in the past been a priority for ESM systems. Thus they are frequently not as good at detecting such radars as they could easily be, and it is suspected that the operators are similarly not as well trained as they might be in using their equipment to detect LPI radars.

## 2 Interception by current ESM systems

In this Section we establish the baseline scenario including parameters of the radar and ESM systems. This allows us to speculate on likely technological advances and the effect they have against the background of system performance at today's standards.

The baseline scenario is a general-purpose ESM receiver architecture using an instantaneous frequency measuring (IFM) circuit after a receiver with an intermediate frequency (IF) bandwidth of a few gigahertz (GHz). An antenna with relatively low gain normally precedes such a receiver, so that the combination has a high probability of intercepting signals over a wide range of frequencies and directions of arrival. As is well known, these systems have a wide video bandwidth, of the order of ten megahertz (10 MHz), so that pulse emitters can be resolved by the time of arrival of their pulses. They are thus inherently limited in sensitivity by the combination of the wide IF bandwidth and the wide video bandwidth. Radars such as frequency modulated continuous wave (FMCW) LPI naval navigation radars can be optimised against such a receiver because the ESM system is primarily sensitive to peak power levels, whereas, with a matched filter, a radar's sensitivity is proportional to the mean transmitted power level. The baseline radar for the comparison will thus be FMCW. The different behaviour of other high-duty-cycle radars will also be considered in subsequent sections. The range at which 100% probability of intercept can be achieved against the main beam of the radar will be taken as the baseline measure of performance, although the importance of sidelobe detection will also be discussed. The simple baseline uses the parameters listed in [Tables 1 and 2](#). The derived performance figures are based on a commonly reported calculation described in [\[1\]](#):

The radar's incoherent gain assumes a dwell of 5 ms (40 rpm scan rate with 1.2° beamwidth), plus the effect of scanning losses, while its other losses are quite low because

**Table 1: Performance of the baseline radar**

Mean transmitter power	1 W
Antenna gain	30 dB
Antenna sidelobe level	−35 dB w.r.t. main lobe
Effective radiated power (ERP)	60 dBmi
Frequency	9 GHz
Integration time	1 ms (1 kHz bandwidth)
Target RCS	100 m <sup>2</sup>
Received power at 20 km range	−125 dBm
Noise figure	4 dB
Noise floor	−144 dBm
Incoherent integration gain	4 dB
Losses	4 dB
Signal to noise ratio at 20 km range	15 dB
Agile bandwidth	100 MHz

**Table 2: Performance of the baseline ESM system**

ESM receiver antenna gain	0 dB
IF bandwidth	2 GHz
Video bandwidth	10 MHz
Effective bandwidth	200 MHz
Noise figure	10 dB
Noise floor	−80 dBmi
Processing losses	3 dB
Minimum signal-to-noise for detection	17 dB
Net sensitivity	−60 dBmi
Incident power density from 60 dBmi at 2.5 km	−19 dBm/m <sup>2</sup>
Effective aperture	−41 dBm <sup>2</sup>
Received power at 2.5 km	−60 dBm

the radar design is very simple and is well matched to the transmissions. The ESM receiver has a lower antenna gain and higher noise figure than might be expected, but these are driven by the need to be able to operate over very wide bandwidths in the presence of many simultaneous transmissions.

It can be seen from [Tables 1 and 2](#) that the radar can detect its target at 20 km range, whereas its transmissions can only be intercepted at 2.5 km. Hence the radar can detect the ship at many times the range at which it can be detected by the ESM equipment. If the baseline is replaced by a pulsed radar with 0.1% duty cycle, the peak power will be increased by a factor of 1000 and the free-space intercept range increased by about a factor of 30. In other words the ESM as depicted in [Table 2](#) will easily detect the radar emissions before the radar system detects its target.

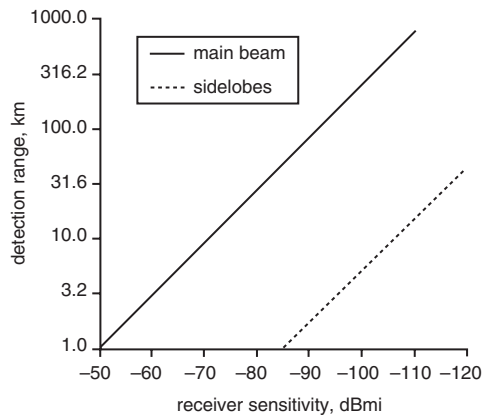
If the radar system were required to detect a smaller target, for example an aircraft, with an RCS of 1 m<sup>2</sup>, at 10 km range, the transmitter power would have to be increased to 6 W, assuming the same antenna gain. The intercept range of the ESM system would then be increased to 6.3 km, which is starting to approach the range at which the target could be detected. It can therefore be seen that the effectiveness of LPI performance is strongly influenced by the radar cross-section of the target to be detected as well as the parameters of the emitted waveform.

In addition, it may be noted that measured intercept ranges from commercial ESM systems against radars such as that outlined above are frequently only of the order of a few hundred metres. That is to say the measured sensitivity may be an order of magnitude less than its theoretical value. This is due to the relatively poor specification of system components. It would, however, be most unwise, when designing and operating a radar system to ignore the possibility that the intercept receiver may be able to meet its theoretical performance.

## 3 Future ESM systems

In this Section we consider likely improvements that will be made to future ESM systems and compute the impact this has on radar detection ranges and ESM intercept ranges. The generic systems described have been derived from research and development and consequently will be consistent with systems quite likely to appear on the market.

Thus the design and analysis of the LPI performance of a radar must not be restricted to its performance against a single type of ESM receiver. It should also consider the



**Fig. 1** Variation of intercept range with sensitivity of intercept receiver

types of intercept receiver which may appear in the future, such as channelised receivers offering greater sensitivity and other more sensitive receiver architectures such as superheterodyne (or superhet). The possibility that receivers might be developed specifically to detect a particular radar must also be considered. Figure 1 extends the analysis in the previous Section to show what free-space detection range may be achieved against the baseline radar, assuming that line-of-sight is available. Here detection range is plotted against receiver sensitivity for mainlobe and average sidelobe levels.

It may be noted that in fact the sidelobe detection range is in some ways a more 'robust' parameter than the mainlobe detection range, because the latter depends on the mainlobe gain, whereas the sidelobe gain will generally be of the order of  $-5$  dB even for very different values of the mainlobe gain.

It is clear that although more sensitive receivers could readily increase the detection range against the mainlobe of the radar, they will still find this much harder against the sidelobes, or alternatively, against a lower power mainlobe. Indeed this has driven designers to produce radar antennas with very low sidelobe levels. It can be seen from Fig. 1 that any free-space detection range is possible, given a sufficiently sensitive receiver. We now consider the advanced systems and compute the improved sensitivity they potentially offer to examine further the relationship between the radar and ESM systems.

This analysis must also consider that the intercept receiver may increase its sensitivity at the expense of reduced probability of intercept (PoI), for example by using a scanning dish antenna. This is a viable approach if the time for which the radar transmits is still greater than the time the scanning dish needs to achieve an intercept.

It is also noted that the PoI of such narrowband, narrowbeam, receivers can then, in principle, be regained by constructing a parallel array of such receivers, to cover a wide range of frequencies and directions. The limitation of this approach is the cost of procuring and maintaining such a system. Hence it could therefore be concluded that the ultimate sensitivity of the intercept receiver, and hence the ultimate limit on the LPI performance of the radar, is probably driven by economics and operational factors rather than by physics. We now consider more advanced ESM receiver systems.

### 3.1 Channelised receivers

ESM receiver techniques are now becoming available which offer greater sensitivity than the 'baseline' system

described in the previous section, by dividing the IF bandwidth (of 2 GHz in the baseline) into a large number of narrow channels. For example a sensitivity improvement of about 20 dB is possible using a channel bandwidth of typically 10 MHz and lower noise figure and losses than the baseline IFM-based system. The detection range against the 'original', 1 W version of the radar will then be increased to 25 km, i.e. it will be approximately equal to the baseline radar's detection range. The tactical implications of using such a receiver in a maritime environment have been further analysed in [2].

A potential counter to this is the pseudonoise radar. This can have a very high instantaneous bandwidth and thus the intercept range will be reduced if the transmission bandwidth is greater than the channel bandwidth. This is due to the signal in any one channel potentially being below the detection threshold, even if the total power (which is spread over several channels) exceeds it. The linear FMCW waveform does not have this advantage because the signal is not instantaneously wideband and in any practical scenario the received signal will 'dwell' in a channel for a period longer than the reciprocal of the channel's bandwidth and so will be detected. However, if the ESM is to recognise the succession of detections in adjacent channels as coming from a single wideband FM signal, it will still require processing designed specifically to do so, although such algorithms are in any case required to process wideband chirped pulse waveforms.

Overall, it is clear that the intercept range of advanced ESM systems can and will significantly increase and hence present a real challenge to future radar systems.

### 3.2 Superheterodyne receivers

A lower-cost alternative to the channelised receiver is to use a superheterodyne receiver which uses filtering and mixing to translate the signal to a lower intermediate frequency (IF). This has the advantage of enabling a narrowband channel (with higher sensitivity) to be tuned over a desired operating range. Superheterodyne receivers are also able to analyse one signal at a time without interference from signals close in frequency and hence are suitable for emitter identification. This form of receiver can be especially useful if a search is to be made for a specific radar type.

The sensitivity of the superheterodyne receiver can be estimated by considering the optimum search strategy to find a radar with an agile bandwidth of  $F_1$  MHz and a dwell time  $T$ . The simplest case is to assume that the radar transmits over a relatively narrowband during the dwell, but the band may be anywhere within  $F_1$ . In that case, to ensure 100% probability of intercept, the intercept receiver must sweep over the band  $F_1$  in time  $T$ . If the receiver has an IF bandwidth of  $F_2$ , then the intercept receiver must dwell in one frequency 'band'  $F_2$  wide for a time  $T_2 = T \cdot F_2 / F_1$ . In order to obtain optimum sensitivity,  $T_2$  must be greater than  $1/F_2$  (although a conventional spectrum analyser dwells for about an order of magnitude longer than that to obtain accurate amplitude measurements). If we take the lower limit of  $T_2$ , we can solve for the optimum value of  $F_2$ ,

$$F_2 = \sqrt{(F_1/T)} \quad (1)$$

For example, for our baseline system,  $F_2 = \sqrt{(100 \text{ MHz}/5 \text{ ms})} = 141 \text{ kHz}$  and the sweep rate will be  $2 \times 10^{10} \text{ Hz/s}$ . In this case the FMCW signal will be detected once as the intercept receiver sweeps past the frequency containing the signal. If the signal is instantaneously wider band, the energy will again be spread across a number of receiver channels, so more opportunities for detection will appear,

but at lower power levels. However, it will be very difficult to distinguish between the radar being sought and any others transmitting in the same band at the same time with this type of receiver.

If still greater sensitivity is required, it can be obtained by slowing down the sweep, which means that the whole agile bandwidth will not be covered on one dwell. The process of intercepting the radar in this case has been modelled by a Poisson distribution, for which the probability of failing to make an interception is given by

$$(1 - p_i) = e^{-n\pi} \quad (2)$$

Therefore

$$p_i = 1 - e^{-n\pi} \quad (3)$$

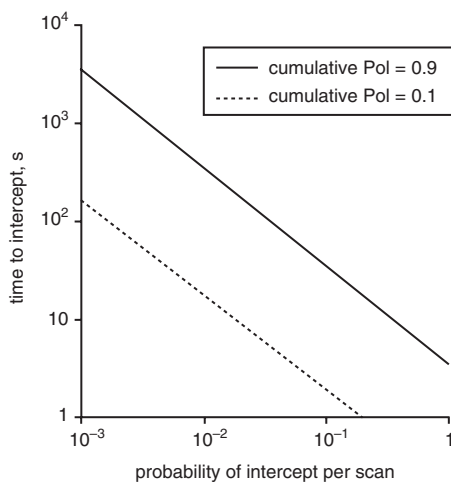
where  $p_i$  is the probability of intercepting the radar,  $n$  is the number of opportunities for interception and  $\pi$  is the probability of interception on one opportunity. For example if the bandwidth is half the 'optimum' value,  $\pi = 70 \text{ kHz}/100 \text{ MHz} = 7 \times 10^{-4}$ . The 'dwell' of the intercept receiver in any one frequency interval will be  $14.3 \mu\text{s}$ , so 350 channels will be searched during the 5 ms radar dwell, so  $n\pi = 0.25$  and thus the probability of intercepting the radar is reduced to 25%.

If the radar is agile from sweep to sweep within the dwell, then the detection of the radar becomes probabilistic and although  $n\pi = 1$ ,  $p_i$  is only 63%. As another example, if we require  $p_i = 90\%$ , we need  $n\pi = 2.3$ , so we must complete 2.3 sweeps of the RF bandwidth during the dwell time, increasing the receiver bandwidth and reducing the detection range against the radar by a factor of  $1/\sqrt{2.3}$ .

Thus overall it can be seen that there is a steep trade-off between detection probability and sensitivity. The more general shape of this trade-off is shown in Fig. 2, with comparative intercept times for the baseline radar being shown.

The two cases shown in Fig. 2, for 90% and 10% cumulative PoI show the time, respectively, until the interceptor can be reasonably sure of finding the radar, and the time for which the radar can transmit and still be reasonably sure that it has not been detected. The separation between these lines (approximately a factor of 20 in time) highlights the important difference between being (reasonably) sure that a radar system will be detected, and being (reasonably) sure that it will not be.

For example, assuming a cumulative probability of intercept of 0.1, we can say that the radar will remain



**Fig. 2** Effect of probability of intercept on time to intercept the radar

**Table 3: Sensitivity of the superheterodyne receiver**

Baseline receiver sensitivity (from Table 2)	−60 dBm
Lower losses	−3 dB
Lower noise figure	−4 dB
Narrower bandwidth	−22 dB
Net sensitivity	−89 dBm

undetected for a period of 10 s when the probability of intercept per scan is approximately 0.02. However, if the probability of intercept per scan is increased to 0.2 then the radar will be detected in less than 1 s. Consequently it is concluded that the radar and ESM system specifications will determine the specification of these probabilities (which themselves will vary). They are crucially important in establishing intercept likelihoods even in the somewhat idealised and simplified representations described here.

It is normally not practical to 'tune' the IF bandwidth to match the optimum detection characteristic against the radar. Mismatches of say 10 dB may be expected between the theoretical and practical sensitivities of the superheterodyne system, unless the receiver has been specifically designed to intercept a particular radar. We may assume that a practical receiver will have a bandwidth of perhaps 1.4 MHz, rather than the idealised bandwidth of 140 kHz. Table 3 shows the sensitivity of the superheterodyne receiver compared with the baseline system. It clearly indicates that significant improvements are possible.

Thus even in the 'non-tuned' case the receiver outlined in Table 3 would still detect the main beam of the baseline radar, in free space, at 70 km range, i.e. considerably greater range than that at which the radar can detect its target. Again this highlights both the sensitivity and variability of performance indicated by these computations.

### 3.3 Derivation of the matched incoherent receiver (MIR)

A similar effective bandwidth to that of the superheterodyne receiver described above, in this case  $2\sqrt{(F_1/T)}$ , is obtained if a radiometric receiver is built to detect the radar. This receiver has an RF bandwidth equal to the radar's agile bandwidth of  $F_1$  and a video bandwidth equal to the reciprocal of the dwell time  $T$ . Although the design of such a receiver is specific to a particular radar type, this design rule can always be applied to the detection of a particular radar. It probably represents the 'worst case' (from the radar operators perspective) intercept scheme against the radar and although such a receiver is unlikely to exist in practice, it represents a good baseline against which the robustness of the LPI performance of the radar can be assessed. However, it should be noted that in the future the enormous growth in computing power makes it feasible for a parallel processor to carry out matched filtering in a number of channels to combat a number of potential threats simultaneously. Because this receiver would be matched to the RF and information bandwidths of the radar, but not to its actual transmitted waveforms, it may be referred to as a 'matched incoherent receiver' (MIR). This is because it still does not match to the phase of the signal as does a proper (coherent) matched receiver. Moreover, the radar no longer has the advantage of a mismatch between its bandwidth and that of the intercept receiver, only the advantage of knowing its own waveform and which part of its agile bandwidth it is actually using at any given time.

For our baseline example, the MIR would have an effective bandwidth of 200 kHz, making it 30 dB more

sensitive than our baseline IFM-based receiver. If we continue to assume the 7 dB improvement over the baseline due to lower losses and noise figure which was assumed for the channelised receiver and the superhet, the MIR will have a sensitivity of  $-97$  dBm, giving it a free-space detection range of 177 km against our baseline radar design.

It can be seen that it is generally possible to postulate a realistic intercept receiver that can detect the main beam of our radar at very long ranges (if it is cost-effective to make it). Greater sensitivity may still be desirable in order to detect transmissions from the radar's side lobes, as discussed below.

### 3.4 Increased intercept antenna gain

Any substantial additional increase in the sensitivity of the intercept receiver, beyond that of the MIR, has to come from increasing the antenna gain. Such an increase may indeed be useful to the intercept receiver, since in practice there are a significant range of radar tasks which can be performed with a mean ERP of 40 dBm or less. Such an increase in sensitivity either requires a major increase in the cost of the receiver, since multiple channels are needed, or else the intercept probability is reduced, i.e. the time to intercept is increased. Although signal-processing costs are being reduced all the time, RF channelisation also still requires increased RF and microwave complexity. Note also that as the nominal detection range increases, it becomes increasingly unlikely that line of sight can actually be achieved over this range in many instances.

### 3.5 Sidelobe detection

Many scenarios may also require detection of the transmissions from the radar's side lobes. Examples of such cases would be:

- (a) the radar's mainlobe never looks at the intercept receiver;
- (b) interception of the sidelobes is required to try to perform intelligent jamming into the radar's side lobes;
- (c) it is desired to attack the radar using an anti-radiation missile (ARM) requiring more frequent guidance updates than can be provided by mainlobe intercepts alone; or
- (d) it is required to use the radar's transmissions as a non-cooperative emitter of opportunity for a bistatic radar, in which case continuous monitoring of the emissions would be highly desirable for the intercept system.

If the mean sidelobe level is assumed to be 35 dB below the mainlobe level (i.e.  $-5$  dBi in the baseline example), then this would reduce the intercept range by almost two orders of magnitude. As current radar antennas routinely achieve sidelobes at this level, this presents a real challenge to the ESM system.

### 3.6 Probability of exploitation

So far, the analysis has considered only the detection of the radar signal, and not the extraction of any further information that would enable the interceptor to exploit the transmissions. We may tackle the problem of assessing the potential for exploitation of the radar by considering the information that can be extracted from the waveform.

Following Shannon's theorem [3]

$$C = W \log_2(1 + S/N) \quad (4)$$

where  $C$  is the channel capacity in bits/second,  $W$  is its bandwidth and  $S/N$  is the signal to noise ratio. In our case, if  $W$  is set to 1 then  $C$  becomes the capacity in bits per interception. For the assumed threshold level of 17 dB

signal to noise, each interception may be assumed to provide the opportunity for extracting 5.7 bits of information about the emitter. We may assume that in order to exploit the transmissions, we need the following information about it:

scan timing, i.e. where the radar is pointing at any time;  
carrier frequency;  
modulation bandwidth;  
signal duration; and  
synchronisation, i.e. when the modulation pattern starts.

If each of these parameters must be known to 4 bits precision, i.e. a bit better than 10% accuracy, we need 20 bits of information to characterise the radar, although this does not include trying to replicate its waveform in any detail. The scan timing and RF frequency can readily be discovered from the way in which the intercept is made, although the latter information is in fact lost by the MIR. This information would therefore effectively be obtained from multiple looks at the receiver output, some of which would indicate that the signal had been detected, and others of which would indicate that it was not present. This would leave 12 bits of information to be recovered from the signal, requiring 36 dB signal to noise ratio. In a more conventional intercept receiver this sensitivity is achieved by obtaining multiple 'looks' at the signal, using a receiver with a wider bandwidth than the signal's information bandwidth.

The problem with attempting to 'match' the intercept receiver, so as to gather all the energy into one 'look' to detect the target, is that it is more efficient in energy terms to obtain information from separate 'looks' at lower signal to noise ratios. For example to send 8 bits of information in one go requires 24 dB signal to noise ratio in the channel's information bandwidth. To send it in two 4-bit messages requires twice as much time, but only 12 dB signal to noise ratio, a saving of 9 dB in the amount of energy used.

It may be noted in passing that the true matched filter [4] removes all the modulation information from the signal, leaving only the information about the energy spectrum. The MIR also removes the modulation information and it may be a fundamental fact that optimising the detection sensitivity involves removing as much as possible of the information-bearing capacity of the original waveform, by whatever means the filtering is achieved.

#### 3.6.1 Sensitivities required for signal exploitation:

We assume, conservatively, that the process of 'coding' the information onto the radar waveform and 'decoding' it in the receiver is 6 dB less efficient than a typical communications channel, which may itself be assumed to be 6 dB less efficient than the Shannon limit [5]. Then we may in practice require 48 dB signal to noise ratio to recover the required information from the signal from the MIR. We have not made any assumptions about how this may be done, but we can note this is approximately equivalent to removing the 30 dB increase in sensitivity obtained by going from an IFM to an MIR receiver. We may hypothesise that the channelised receiver achieves an intermediate exploitation performance by being less 'lossy' than the IFM in recovering the information, but that it will require additional signal to noise to 'stitch together' the outputs of the different channels to recover all the information required.

The above discussion brings us on to the problem of exploiting the radar's transmissions. The simple radiometric detector is able to cope with any waveform, but at the cost of destroying most of the information contained within it. This makes it unsuitable for use in a busy environment, but it

may be suitable during nominal 'radar silence' when very few emitters will be present.

In fact, in busy environments, it can be argued that the best way of transmitting covertly is to make the transmissions look like a conventional marine radar, or like an aircraft weather radar. Thus they may not be noticed. If an LPI waveform is detected, it is clearly not coming from an innocent source.

### 3.7 Special-purpose intercept receivers

The possibility that a receiver may be built specifically to detect a particular radar system has been considered above from a theoretical point of view. Such a receiver design may indeed be a real possibility if the radar poses a sufficient threat and its waveform is sufficiently simple to detect. Examples of such receivers are those built to detect police speed radars, or the use of those same systems to detect military CW radars [6]. This is a possibility which should be considered in the design of any radar for which LPI is important. The way for the radar designer to tackle this threat is to aim for the situation where the radar remains undetectable to general-purpose intercept receivers, but the complexity of the waveforms is such that the development of a special-purpose intercept receiver is not cost-effective. However, Ho *et al.* [7] discuss detection of the modulation on a PSK signal, showing that it is possible to envisage techniques for de-spreading even relatively sophisticated modulations.

Techniques have also been proposed to detect linear FM and measure its sweep rate by cross-correlating the signal with a delayed replica of itself [8, 9]. This process can be viewed as generating a beat frequency proportional to the product of the chirp rate and the delay time, which can be analysed using a Fourier transform. Since there is noise on both the delayed and non-delayed signals, i.e. there is no clean reference, then that technique will not be expected to be more sensitive against weak signals than a conventional square law detector with the same integration time, although it will give extra information.

Trying to match the ramp of an FMCW radar is not a good idea: the ramps are seldom exactly linear and the lower the integration bandwidth the more finely the sweep rates have to be matched, the more the PoI is reduced. This is, in fact, the basis of the way FMCW radars, for example for automotive applications, can reject interference from other similar radars.

### 3.8 Prevention of use as a bistatic transmitter

It is clear that the techniques that are required to use the radar as a non-cooperative emitter for an opportunistic bistatic receiver are very similar to those that are required to identify and exploit it for other purposes. In particular, if the knowledge of the scan pattern and of the transmitter timing can be hidden, then synchronisation becomes very difficult. Adaptive timing will also help ensure that even if the pattern is discovered the intercept system will have to continually re-acquire it whenever it is changed again. If the directionality is removed from the transmitter pattern, see, for example, [10], then any opportunistic bistatic receiver will be forced to have a directive receiver, which will greatly increase its complexity, since it can no longer rely on the transmitter to provide its direction information. In this situation, making good use of prior knowledge about the radar's characteristics can become more important than acquiring that information in real time. Indeed techniques have been reported that transmit an additional waveform in the sidelobes such that the exploiting radar is unable to extract

a suitable reference waveform for bistatic correlation [11]. Currently there are very few operational bistatic radar systems and none addressing military applications. However, there are a small number of systems that are under development and hence bistatic denial is likely to assume greater importance in the future. A detailed analysis is outside the scope of this paper and the interested reader is referred to [11].

## 4 Radar design to minimise probability of interception/exploitation

The subject of designing a radar to minimise the probability of its transmissions being intercepted is now considered. The previous parts of this paper have discussed the physics of detecting the radar, but this section discusses the engineer's response to trying actively to do something about it.

There is, indeed, the wider issue of how far one should actively try to reduce detectability, since this will generally lead to compromises in either the cost or the performance of the radar, or both. The engineering decision is itself a trade-off between the benefits to the user of reducing the exploitability of the transmission and the effects on cost and overall performance. The decision as to how far to reduce the detectability must thus be made on a case-by-case basis and hence cannot be generalized in a way which would be suitable for a paper such as this. For the purposes of this paper we will discuss only the technical aspects of the subject, which can be subjected to such a generalisation.

### 4.1 Increased RF bandwidth as a defence against more sensitive receivers

It can be seen that whereas increasing the agile bandwidth does not decrease the detection performance against a general-purpose receiver, it provides a powerful method of decreasing the potential sensitivity of the matched incoherent receiver, which provides the ultimate limit of sensitivity against the radar. It also provides a defence against detection by, relatively narrowband swept superhether receivers.

Following the formulation of the matched incoherent receiver, increasing the bandwidth will reduce the sensitivity by the square root of the increase and hence reduce the detection range by the fourth root, so significant decreases in detectability will require large increases in the bandwidth – for example, in the baseline scenario an order of magnitude increase in bandwidth would lead to a 5 dB decrease in the sensitivity of the incoherent receiver, so this will be less effective than might be expected. On the other hand, if RF agility is used against a scanning receiver, an order of magnitude increase in the agile bandwidth would decrease the detection probability and hence increase the intercept time, by a straight order of magnitude, which could be very significant against a non-optimum (i.e. more general-purpose) intercept receiver.

It is also noted that according to the concept of the MIR the decrease in intercept range is predicated on coherent integration by the radar. This is because the radar and the ESM will both increase their sensitivity by the same amount if incoherent integration is used by the radar. Coherent integration over a wider bandwidth, with the same integration time, which increases the time-bandwidth product, requires an increase in signal processing capacity at least equal to the increase in bandwidth.

### 4.2 Removing the scan modulation

After spreading the transmitted energy over a longer time (i.e. using CW waveforms) and spreading it over a wider

bandwidth, the other technique for reducing the energy density is to spread it in space, i.e. to reduce the transmit antenna gain. For search radars this can be done if the energy is spread over a wider angle. This allows the receiver to maintain a longer dwell time. If a separate phased array receiver is used, this can form multiple narrow beams, so the radar's power budget is unaffected. This principle is well known [10]. The long dwells have the side-effect of allowing fine Doppler resolution. In fact they demand it, and so may place significant constraints on the close-to-carrier stability of the radar and on the ability to integrate coherently over long periods, i.e. to be able to cope with changes in target velocity during that period. If shorter integration times are joined incoherently, then the radar's essential advantage over the ESM, its ability to perform coherent integration, is reduced.

In principle the ESM receiver can also increase its integration time indefinitely, but in practice it will become increasingly difficult for it to distinguish the radar signal from changes in its own noise floor or other signals. Removing the scan also removes one of the few parameters left which could identify the radar. Quasi-CW modulation has removed the time-of-arrival information, frequency agility has removed RF frequency as an identifier, removal of the scan removes scan timing information and all that is left, even if the radar can be detected, is the instantaneous bandwidth and the modulation on the pulse.

As a simple example, if a radar with  $3.6^\circ$  beamwidth and  $360^\circ$  scan was redesigned to use an omnidirectional antenna, the transmitted power density would be reduced by 20 dB, with the same power being radiated over the whole coverage area rather than over the beamwidth. The radar could theoretically recover the sensitivity by increasing its integration time by 20 dB. The effect on the detectability could, for example, be enough to nullify the gain to the intercept receiver of lowering its threshold from  $-60$  dBi to  $-80$  dBi, as described in Section 3.1.

However, this technique has limited use if the ESM receiver is required to detect the transmitter sidelobes, since the latter will generally be below the 0 dBi level, which is the minimum mainlobe gain that the transmitter can have. Unless the radar's coverage is hemispheric, the gain even with a non-scanning transmitter is likely to be well above this level. To take the marine radar example in Table 1, a reduction in antenna gain of 20 dB would still leave the mainlobe gain at  $+10$  dBi, compared to a typical sidelobe level of  $-5$  dBi. Sidelobe interception would in any case be less important since an increased coherent integration time reduces the radar's scope to use frequency agility to spread its spectrum between coherent processing intervals.

**4.2.1 Effect on opportunistic bistatic receivers:** If the directionality is removed from the transmitter pattern, then any opportunistic bistatic receiver will be forced to have a directive receiver, which will greatly increase the complexity of the system, since it can no longer rely on the transmitter to provide direction information. Another way of obtaining bearing information, in the absence of directionality either of the transmissions, or, of the reception is, of course, by triangulation if multiple transmitters or receivers are available. This may be needed in any case to locate the position of the transmitter of opportunity. The use of multiple receivers for radar netted systems is further discussed in [12].

**4.2.2 Effect of removal of identification information:** Removal of the scan modulation will

make it potentially harder to resolve two radars on similar bearings as there will be one less discrimination parameter.

Injecting false targets into the sidelobes to make them appear in a direction different from that of the jammer will probably become impossible unless the geometry allows near-field effects to be significant so that 'cross-eye' jamming could be used to manipulate the wavefront. Otherwise the receiver beamformer will always correctly indicate the direction from which the jamming is coming. The beamformer may even be able to form nulls in that direction specifically to reject such signals. This technique would appear therefore to be able completely to prevent this particular jamming strategy rather than just mitigate its effects.

It may be noted that if the scanning is removed, jamming and interception no longer require knowledge of the radar's scan timing, although that was a parameter which was straightforward to obtain, even from the MIR.

### 4.3 Hide the radar signal in other transmissions

As has been mentioned above, if an ESM receiver detects a radar transmission in a relatively clear part of the spectrum, it is likely to attract much interest. If, however, the signal is detected in a cluttered spectral environment, then the time taken to identify and hence exploit the signal will be greater. This can be used to the radar's advantage especially if the radar waveform is designed to match or 'look like' the other transmissions in the local spectrum. In some, lower frequency, cases mobile phones can provide such a 'background' within which the radar can be hidden if operating on the same frequency. For example an LPI radar system can adjust its transmitted power to be just sufficient for the desired detection range. This will maximise the likelihood that it will be confused with the transmissions from a mobile phone base station. The precise location of base stations, radar and ESM will determine actual performance. It should also be noted that this strategy will reduce performance in the presence of target fading. Care must also be taken to minimise mutual interference which will also result in a reduction in radar performance. This may require use of waveform coding as a means of differentiating the two sources of transmission. Ultimately a tactical judgement must be made as to whether the improved LPI performance is worth the potentially reduced radar detection performance.

## 5 Effects of using different waveforms

This Section considers the effective LPI/LPE performance of some different waveforms which have been proposed. It should be stressed that to be of any practical importance, a difference in performance will generally have to be quite substantial. It must outweigh any additional cost and any performance constraints arising from its use and must be able still to give a significant improvement under different scenarios. If the 'average' improvement is masked by the effect of the variations in the scenario, for example by changes in the lines of sight and the required intercept times, then the theoretical benefits could be of little tactical value.

In general, deterministic waveforms such as FMCW ought to be more detectable than more 'noise-like' waveforms because they are specified by fewer parameters and once part of the waveform has been detected, the 'next move' in the sequence can also be predicted. It is believed that an implicit assumption of this sort lies behind many assumptions that 'noise-like' waveforms are more LPI than more deterministic waveforms of the same time-bandwidth

product. Here we examine this issue with somewhat more care than is usually taken and will examine aspects such as:

- (a) the practical benefits of deterministic waveforms for interference rejection, range side lobe suppression and simplification of the signal processing;
- (b) the trade-off between accuracy in predicting the waveform and improved intercept performance; and
- (c) the number of possible waveforms through which a receiver would have to search—how many ‘good’ noise-like waveforms are there?

The common arguments in favour of noise-like waveforms are expressed in [13, 14].

### 5.1 Techniques proposed for detecting LPI waveforms

A commonly proposed technique to detect LPI waveforms is auto-correlation. This is actually strongly related to radiometric detection. The latter would typically use a wide RF bandwidth, a square-law detector and a low-pass filter. This is the same as auto-correlation with zero delay, in which form it is a well known way of detecting biphase modulated signals since, of course, it removes the modulation. For an FMCW radar a slightly more sophisticated approach is to multiply together delayed and undelayed versions of the signal. The output will be a sine wave with a frequency equal to the product between the sweep rate of the signal and the time delay in the receiver, so a fast Fourier transform (FFT) after the multiplier will enable the sweep rate to be recovered, since the beat frequency can be deduced and the delay is known. This technique has the potential advantage over the general square-law detector in that the detected signals are AC rather than DC, and thus, in an analogue receiver, are not susceptible to corruption by DC offsets in the system, as well as providing some information about the waveform. However, the sensitivity of the detection of the signal is still poor.

For weak signals, with low signal to noise ratios after the detector, the signal to noise ratio in the much wider bandwidth before the detector will be less than unity. The detector output will thus be dominated by the smoothed auto-correlation of the noise and the crosscorrelation of the noise and the signal, rather than by the desired signal, so the sensitivity is still the same as that of the square-law detector.

### 5.2 Benefits of a deterministic waveform

The most obvious advantage of the classic ‘pulse’ waveform is that it allows targets at different ranges to be perfectly separated. In fact this is possible in any waveform for which the spectrum is suitably shaped, but for some waveforms, such as linear FM or pure noise, shaping the spectrum may require the acceptance of a mismatch loss. Conventional approaches to using PSK waveforms, for example, give relatively high sidelobes compared with linear FM waveforms, but this is not believed to be a fundamental limitation.

A lesser, but also important, benefit of a pulse waveform is the ability to reject interference. Signals from other sources can also appear as ‘pulses’ and hence as targets, however, they can be rejected after detection by looking for consistency of the returns from spoke to spoke (i.e. scan to scan), which will not occur if the pulse repetition frequencies of the radar and the interferer are different.

FMCW waveforms can similarly reject other FMCW radars and can also reject pulse waveforms [15]. In fact, if the interfering signal can be processed as another target or

else be rejected completely, then it can be removed. Interference from noise-like radars will, however, just look like noise jamming (as will any CW interference when received by noise-like radar). The more ‘random’ the signal, the more likely it is to lead to interference problems. The higher the power received the worse the problem.

One way of trying to detect an unknown waveform is to try to guess what it is and correlate any received signals with that guess. If the waveform is not perfectly known, the correlation can be against a number of samples of the waveform. This cannot be used as a ‘generic’ way of trying to detect LPI waveforms because if one tries a correlation with all possible waveforms, one of those ‘possible’ waveforms will always be the exact pattern of the thermal noise in the receiver over the same time interval. The spurious ‘detection’ of the noise will cause complications if the input signal to noise ratio of the true signal is less than unity. Detecting deterministic waveforms by this approach is easier than for non-deterministic waveforms because small errors in the estimate of the waveform will usually cause predictable, proportional, degradation in the detection efficiency, whereas such errors, including Doppler effects, could completely destroy the correlation of more noise-like waveforms. However, for so-called ‘deterministic’ waveforms, the ability to reconstruct the radar’s signal processing gain may be limited by imperfections in the radar signal. To take the linear FM waveform as an example, the ‘linearity’ need only be good enough to avoid spreading the target; for example, a missile seeker may only need a linearity of 1% or so, so the waveform may differ by up to 1% from the nominal value, which means that the maximum processing gain which could then be obtained by an intercept receiver would be about 20 dB. This is the same as the gain which the MIR would produce for a time–bandwidth product of 40 dB, so there may be little benefit in practice from following this approach; of course, the more precise the original waveform, the more efficiently it can be intercepted.

The greater the number of possible waveforms, the greater the chances of a false alarm. We make an approximation that it requires an increase in the detection threshold of about half a decibel to reduce the false alarm rate by an order of magnitude [16]. Even if 10 000 waveforms need to be examined (for example this is the maximum number of waveforms with a time–bandwidth product of 10 000), and there are 10 000 possible correlation delays and 100 possible Doppler shifts to be tested, the  $10^{10}$  combinations will only require a raising of the threshold of 5 dB to maintain the false alarm rate.

If it is suspected that the radar uses a pseudorandom waveform, in theory an exhaustive search of possible waveforms could be attempted. This is probably not currently possible, but, presumably, will be one day. In practice, however, the choice of waveform may be reduced, since one requires a maximal-length sequence (e.g. a binary code of all ‘1’s or all ‘0’s would not give the required resolution) and some waveforms are sufficiently close that only one of a set may need to be tried.

The number of combinations will still be large, however, and exhaustive searching of high time–bandwidth waveforms may not currently be practical, but the power to do this digitally may become possible in the future. For example, if a correlator can correlate a waveform with 1 ms integration length in real time, it could search 10 000 waveforms in only ten seconds.

The above discussion ignores the practicalities of converting the above into an effective probability of intercept. In some circumstances a single intercept every

ten seconds may be acceptable, in others it would not. It also ignores the issue of how the intercept receiver first determines the RF bandwidth and integration time of the waveform it is trying to intercept, but it does suggest that pseudonoise waveforms are not necessarily immune from brute-force attempts to correlate them, which strengthens the case that it is naive to assume that pseudorandom waveforms are necessarily harder to intercept and exploit than are more deterministic waveforms.

### 5.3 Potential benefits and limitations of high duty cycle

It is well known, and, indeed, has been taken as the 'baseline' for this paper, that the use of high duty cycles to minimise the peak power of the radar is a key LPI technique. Although the 'MIR' is insensitive to the waveform used, it is a good LPI technique against any general-purpose intercept receiver with a relatively wide video bandwidth. It is worth noting, however, that the corollary that 100% duty cycle gives the best LPI performance does not necessarily follow. As the duty cycle increases, eclipsing losses become significant until eventually, above at most 50% duty cycle, simultaneous transmission and reception are required, needing sometimes separate antennas, sometimes a reflected power canceller [17] to suppress the transmitter leakage and sometimes both, together with careful, low noise, oscillator design. These will typically degrade the sensitivity by a small number of decibels with respect to a simple radar making maximum use of the power-aperture product. A pulsed radar can give up to about 30% duty cycle without the compromises required by the CW radar. In such a case, going from 30% to 100% duty cycle would only improve the performance by 3 dB, which is generally less than the uncertainties in the 'link budget' from radar to intercept receiver, and so is probably not usually worth while. The effective duty cycle of the pulse system could be reduced to 20% by the need to transmit other shorter pulses to 'fill in' at short ranges. However, the net gain in going from that waveform to 100% duty cycle operation is only 5 dB, which is only on the limit of being significant. With the LPI considerations being fairly well balanced, in such a case the choice of waveform is probably decided by which design is easier to implement in the particular radar. If either two-antenna operation [18] or a reflected power canceller [17] are acceptable, or are attractive for other reasons [18], then CW operation will be chosen. In other cases demands, for example, for simple phased array module design or at operation close to ambiguous ranges might tip the balance in favour of a pulse solution. Generally, it is probably more effective to design the radar system to be pulsed as this makes unambiguous operation easier and enables data rates to be more easily managed, but of course this will increase the probability of intercept.

## 6 Example scenarios

This Section looks at how the different factors discussed in previous sections of the paper interact in particular scenarios. It provides examples of how the needs and advantages of designing a radar to be difficult to intercept may be addressed at a system level and some of their consequences.

### 6.1 Baseline scenario

In the baseline scenario, the ship carrying the radar would remain undetected for as long as it remained more than 2.5 km away from the intercept receiver, but would be

detected as soon as it came within that range. The distinctive FMCW modulation would then be detected and the radar easily identified, since the mismatch between the IFM bandwidth and the radar's integration time would, at least in theory, allow extra information readily to be extracted from the waveform.

### 6.2 MIR with widebeam antenna

The mainbeam of the radar can now be detected at a free-space range of 177 km, i.e. in practice as far as there is line of sight between the radar and the intercept receiver. During periods of radar silence, where any signal is of interest, a single interception would give valuable information. In more 'noisy' scenarios, however, the range would have to come down to a few kilometres again against the mainbeam before the radar could be positively identified, as opposed to just being detected.

### 6.3 MIR with widebeam antenna, sidelobe detection

If the radar operators know the likely bearing of the intercept receiver, they can avoid pointing the mainlobe of the radar in that direction, forcing the intercept receiver to rely on sidelobe detections, at a typical range of only 1.8 km even with the MIR. The direction of the intercept receiver may be able to be deduced, for example, from the bearing of jamming signals.

If the radar must radiate in the direction of the intercept receiver, it may also be able to reduce the transmitted power to 10 mW when looking in that direction. This, in the case of the example maritime radar, would be sufficient for navigation and would have the effect of reducing the free-space intercept range to about 18 km, which may not be adequate for a stand-off intercept system. It should be noted that many radars do not need all of their sensitivity most of the time.

These considerations become critical in phased array radar systems where the spatial properties of transmit beams can be controlled. In principle if the direction of the ESM is known then, if the ESM is not on the platform which the radar must detect, the radar antenna can adaptively place a null in its direction, even when 'scanning'. In this way the impact on detection performance can be minimised.

### 6.4 Simple receiver to 'home in' on the radar

A simple, portable, MIR, which might be used to 'home in' on the radar, would only have a range of 1.8 km against the radar's sidelobes, but could be used, for example, by attackers in a small boat who knew the approximate location of the radar platform.

### 6.5 Detection by MIR with scanning dish

A stand-off system could use a scanning dish receiver: if this has  $10^\circ$  beam width, and a gain of 20 dB, then the detection range against the lower power mainlobe suggested above would be increased to about 180 km, quite sufficient for stand-off operation. The sidelobe detection range would still only be 18 km. The intercept time would then equal the scan time of the dish. The MIR was based on a dwell of 5 ms, so the worst case intercept time is  $5 \text{ ms dwell} \times 360^\circ \text{ coverage} / 10^\circ \text{ beamwidth}$ , i.e. 180 ms, so the mean time will be half this, i.e. 90 ms.

If 90% detection probability were required against a signal with random scan-to-scan agility, this intercept time will be increased to about 200 ms (see Section 3.2) as discussed above. Thus, although greater sensitivity is required to detect the sidelobes at reasonable ranges, the increased gain required is not as great as the ratio of

mainlobe to sidelobe gain of the radar. The intercept time against the mainlobe would be the scan time of the radar, 1.5 s, times 18 times 2.3, for 90% probability of intercept, or about a minute.

If the intercept receiver needs to detect the sidelobes of the radar considered above at a stand-off range of 50 km, the antenna gain would have to be increased to 29 dB. This would increase the intercept times by about a factor of  $(50/18)^2$ , or 7.9 times, to 1.7 s for 90% probability of being detected.

If the transmitter power can be reduced to 10 mW, for short-range detection of large targets, and mainlobe intercepts can be avoided, then larger antennas will be needed to detect it and the mean time before the sidelobes can be detected will now be increased by another two orders of magnitude. That is to say observations could be made for nearly 3 min before there is 90% chance that the radar will be detected, with a 50% chance that it will be detected after 50 s.

If the agile bandwidth of the radar is increased to 1 GHz, this would increase the intercept time by another order of magnitude, so that there would be a 50% chance of its remaining undetected after 8.5 min. The probability of being detected would only reach 90% after 30 min. This detection would still not give enough information to allow intelligent jamming to be performed.

A short surveillance operation could be carried out in this scenario with a low probability of the radar being jammed before the operation was over. There is a fair chance that the radar would remain undetected after a short operation, and for up to 80 s operation there would only be a 10% probability of its being detected. Short periods of radar use may then be assumed to be undetectable, particularly if there is a probability that they can also be masked by other emissions in the same band.

The assumed intercept receiver now has 40 dB antenna gain, so probably some other mechanism would be used instead to increase the sensitivity, such as slow scanning in frequency as well as in angle. This receiver is now closer to a strategic electronic intelligence (ELINT) receiver than a tactical ESM system, so further issues of cost and availability of such systems must be considered when judging the likelihood of this scenario against any particular radar system. Thus overall the judgement of when to switch the radar on and for how long is extremely difficult to make being the balance of probabilities. Table 4 illustrates the close interplay between the radar, the ESM and the scenario. It can be observed that an emitted power level of only 10 mW can be detected at 180 km and a power of 1 W at

only 2 km. This is related to the close interplay between the form and magnitude of the radar emissions and the detection methods used.

## 6.6 Intelligent exploitation

As previously discussed to perform any intelligent exploitation of the radar will require of the order of a further 30 dB of sensitivity. This extra sensitivity could be achieved either:

- (a) by reducing the intercept range to 3 km; or
- (b) by increasing the intercept time to three weeks which would in most cases make the information obtained too late to be tactically useful.

With 1 W transmitter power and a side lobe intercept range of 16 km, the exploitation information would still require 30 min to be acquired. With mainlobe intercepts at 10 mW power, the information could be obtained in 3 min.

It appears therefore that in this low power case, if all the possible low probability of exploitation (LPE) techniques are employed as efficiently as possible, it is possible to make it almost impossible to exploit its emissions within tactical timescales. This is not actually true because better intercept performance could be obtained from an array of high-gain dishes, each dish being backed by a separate channelised receiver. If cost and size are no object, the intercept receiver can always win by using large enough antennas.

## 6.7 Non-scanning transmitter

If the radar system did not scan, but formed 300 receiver beams continuously from an omnidirectional transmission, the mainbeam intercept range would be decreased by a factor of 17 times. However, it would no longer be possible to avoid looking at the intercept receiver and the effect is the same as increasing the sidelobe level by 30 times (15 dB), i.e. the ERP is only 25 dB below that of the mainbeam of the scanning system, whereas the sidelobes of the latter are 35 dB below the peak. If mainlobe intercepts can be avoided, it is therefore better to be able to steer the beam away from them, whereas if this cannot be guaranteed it is better to compromise and use a non-scanning system. A flexible radar design should therefore be able to form a single scanning beam with relatively high power, or a widebeam signal with lower effective radiated power. If possible, it would also be desirable to steer nulls onto the expected directions of the intercept receivers.

**Table 4: Summary of interception characteristics in different scenarios**

Radar power	Detection scenario	Antenna	Intercept receiver	Intercept range	Intercept time	Pol
1 W	mainlobe	wide-beam	IFM	2.5 km	1.5 s	1.0
1 W	mainlobe	wide-beam	MIR	177 km	1.5 s	1.0
10 mW	mainlobe	wide-beam	MIR	18 km	1.5 s	1.0
1 W	sidelobe	wide-beam	MIR	2 km	instant	1.0
10 mW	mainlobe	dish	MIR	180 km	1.5 s	1.0
1 W	sidelobe	dish	MIR	18 km	90 ms	0.5
1 W, agile	sidelobe	dish	MIR	18 km	200 ms	0.9
1 W, agile	mainlobe	dish	MIR	18 km	1 min	0.9
1 W, agile	sidelobe	dish	MIR	50 km, standoff	1.7 s	0.9
10 mW, agile	sidelobe	dish	MIR	50 km, standoff	3 min	0.9
10 mW, 1 GHz BW	sidelobe	dish	MIR	50 km, standoff	8.5 min	0.5
10 mW, 1 GHz BW	sidelobe	dish	MIR	50 km, standoff	30 min	0.9

## 6.8 Tactical implications

The ultimate goal of the engineering application of 'undetectable' waveforms is to provide some tactical benefit to the user of the system.

The exact benefits and their value will be specific to particular systems and particular users, but some general examples of the type of benefits may be given here.

**6.8.1 Marine navigation radars:** It is unlikely that marine navigation radars would be the subject of attack by an anti-radiation missile, direct attack on the maritime platform is more likely, and they would not normally be subject to deception jamming, but their interception can give valuable information about a vessel's movements, particularly in littoral environments where use of the radar is most valuable. Prevention of interception then denies an enemy this information and prevention of exploitation is then manifested as preventing the enemy from distinguishing between the radars on different platforms.

**6.8.2 Submarines:** Similar considerations to those for marine navigation radars would also apply to radars on a submarine, except that the much more severe consequences of detection of the submarine from those emissions place a much greater demand on the ability not to be intercepted, or at least for the platform not to be identified. In this case a radar with the same characteristics as the navigation radar on a fishing boat may in some ways be the best choice.

**6.8.3 Battlefield reconnaissance radars:** Detection of battlefield reconnaissance radars could in itself provide a significant tactical advantage for the detector and, because the system is often more closely coupled to indirect fire weapon systems than a marine navigation radar, there is a greater incentive to attack the radar itself, especially as that may be the only way of finding the vehicle or men using it.

**6.8.4 Aircraft obstacle avoidance radars:** Terrain avoidance radars are used by low-flying fixed-wing aircraft, conferring tactical advantage to the platform, but also giving an opportunity for the platform to be detected. Of course radioaltimeters also fall into this same class of radar. Since these are used by high-value platforms, an opponent has a great incentive to detect, attack, or jam the radar. Low flight profiles will limit the time for which the radar is visible to an intercept receiver on the ground, but reducing the detectability of such radars is known to be important. The AN/APQ-181 radar in the B2 stealth bomber [19] is described as being 'low probability of intercept' for this reason.

Wire detection or power line detection radars for helicopters have been proposed [20, 21] and would fulfil a real need, but for use in a tactical helicopter they would have not to compromise the detectability of the platform. If radar techniques are used for wire detection, they will probably involve low-power, wide bandwidth, millimetre-wave radars, which would be hard to detect because of their spread spectrum and the smaller apertures of millimetre-wave, intercept receivers.

**6.8.5 Millimetre-wave seekers:** Another application of millimetre-wave radars is in seekers for guided shells and small missiles. Here the detection of the radar's emissions would cause little concern to the launcher, but could be vital for the platform being attacked, as it is one of the ways the attacker may be recognised, to be countered, perhaps by deception jamming, if exploitation of the

transmissions cannot be prevented, or alternatively, by physical counterattack. LPI/LPE is therefore a useful addition to the sensor's capabilities in order to forestall some of the potential countermeasures to the weapon.

**6.8.6 Conclusions from discussion of scenarios:** It can be seen from the foregoing that reducing the ability of an enemy to intercept or exploit a radar's transmissions can be useful in a variety of scenarios.

In some scenarios a relatively modest reduction in intercept probability can confer a useful tactical advantage compared with the current situation. This is particularly so in cases like the seeker head, where the enemy must have a high probability of detecting the radar in order to survive. On the other hand, in cases such as the submarine radar, the potential user would have to be very certain that the radar would not be detected before daring to use it.

It may be noted that all the examples discussed involve relatively low-power, short-range radars. It is much harder to achieve any tactically useful reduction in the intercept range of high-power radars, such as airborne early warning (AEW) systems for example, because the high power means that it is relatively easy to detect even the sidelobes, even when relatively good LPI waveforms are used.

## 7 Conclusions

The above examples have analysed the performance of a basic LPI radar system against a series of possible intercept scenarios. This has enabled some general conclusions to be drawn about the design requirements of the radar and its LPI/LPE capabilities, without requiring any detailed information about particular ESM systems. In part this has been achieved by introducing the general concept of the matched incoherent receiver. Conclusions are:

- Analysis of the above examples shows that it is important to design the radar to make it difficult to detect transmissions from its sidelobes.
- Denial of sidelobe detection is particularly useful to prevent an enemy from exploiting knowledge of the radar's parameters, for example by jamming through the sidelobes, which requires knowledge of the current RF frequency and, for intelligent jamming, of the timing of the radar signals.
- It is likewise important to spread the radar's energy over as wide a bandwidth as possible, to hinder attempts to optimise strategies to intercept it.
- Waveforms with wide instantaneous agility are better than those with slow agility against superheterodyne or channelised receivers, but are no more effective than slowly agile signals against IFM or MIR based systems.
- It is not believed that deterministic waveforms, such as FMCW are more easily detected than non-deterministic waveforms, although once detected they are probably easier to exploit.
- It is important to be able to control the amplitude of the radar's transmissions to avoid transmitting more power than is necessary, particularly when looking in sensitive directions. It is always important not to exceed the transmitter power necessary. Reducing the receiver noise figure and the losses is in any case always a better way of improving performance than increasing the transmitter power.
- If the intercept receiver can be forced to scan in bearing or frequency to search for the radar's emissions the purpose of an LPI/LPE design then becomes to reduce the probability that this will occur within the time frame over which the radar is to be used.

One of the problems when using LPI radar is, therefore, that one can never be completely certain that a radar systems transmission has not been detected, nor of whether a radar would remain undetected if it did transmit. The benefits of LPI are therefore balanced between how much benefit the user will get from using the radar, how much an enemy will gain if he detects the radar, and how confident the user can be that the radar will not be detected. These are all tactical judgements, informed by an assessment of the enemy's ESM capability, and in practical scenarios they may be as much influenced by line-of-sight considerations as by the free-space sensitivity of the equipment. The approach to using LPI radar should thus be:

- (a) Assess the tactical situation to determine how to set up the radar to minimise the probability of interception whilst carrying out the radar's task.
- (b) Determine the probability of being detected while performing the task, and the consequences of being detected.
- (c) Decide whether the benefits of using the radar outweigh the dangers of being detected.

It is clear that this decision process cannot be carried out in full by the operators each time the radar is to be used, so the process must be reduced to a series of rules of operation, appropriate for the particular radar and the missions for which it is required. These rules might, however, be assisted by some sort of automatic 'advisor' to perform some of the calculations.

There is no doubt that in some specific cases radar information is of great value, and worth the risk of transmitting, especially if that risk can be judged to be low, whereas in other circumstances it will not be worth the risk of being detected.

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