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RADARS WITH LOW PROBABILITY OF INTERCEPTION

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The arrival of wide band, high duty cycle radars has made it practical to design radars with enough processing gain to detect their targets at greater ranges than those at which their transmissions can be intercepted. This paper looks at the principles of such Low Probability of Intercept (LPI) Radars and illustrates this with a simple quantitative example, comparing the performance of a pulse radar with an Frequency-Modulated Continuous Wave radar. The paper takes as its baseline a receiver using the Instantaneous Frequency Measurement technique, but discusses other possible receiver types, leading to a brief examination of the trade-off between interception sensitivity and intercept time. It is argued that coherent matched filtering is not a good way of trying to intercept an LPI radar and, instead, the virtues of the Matched Incoherent Receiver are discussed, where the pre-detection bandwidth and post-detection integration time are matched to the radar's signals, but the detection is incoherent rather than coherent. The additional strengths which are potentially offered in this area by noise waveforms are also discussed. The importance of the military scenario for the significance of an LPI radar and particularly for the complementary principle of 'Low Probability of Exploitation' are also emphasized.

Keywords: Low Probability of Intercept Radar, Intercept Receiver, ESM.

1. INTRODUCTION

The designation 'Low Probability of Intercept' (LPI) for a radar is intimately connected with the 'contest' between radars and Electronic Support Measures (ESM, Intercept) receivers in a tactical military environment, which was well illustrated in reference 1. The way in which this battle plays out and how it is affected by the design of the equipment, both the radar and the intercept receiver, is best explained by way of typical quantitative examples, but before these are introduced, some points which will define the problem more clearly will be examined.

The description above used the terms 'tactical' and 'military.' This paper is not concerned with 'strategic' (electronic intelligence) issues, such as knowing that a given type of radar exists and what its modes are. Given time, a radar can always be detected. The question is whether the radar can be designed so that it can remain undetected for long enough to give its users a significant tactical advantage. For this reason, the baseline intercept receiver is considered to be an ESM receiver.

This can also be called a 'military' issue since interception is not a concern to civil radars. More significant, is the fact that 'military' operations should now also include actions against smugglers and pirates, who can potentially afford radar detectors, which are manufactured for mariners to detect other radar-equipped craft. There are also low cost marine radars which are readily available which have considerable LPI potential as a side-effect of using waveforms compatible with solid-state transmitters. The term 'military' should thus be taken also to include 'paramilitary' users.

The term 'Low Probability of Exploitation' is sometimes preferred to 'Low Probability of Intercept,' since what is often required by the interceptor is not just to know that the emitter is there, but to be able to do something with the information obtained from it, either to obtain tactically-useful information from its presence or to be able, for example, to jam it. This paper, however, will continue to use the term 'Interception' because this is amenable to more general quantitative analysis. 'Exploitation,' whilst it better describes what is militarily significant, is much more dependent on the operational scenario, which then has as much effect on a technique's effectiveness as does its scientific characteristics.

Other methods of reducing the probability of exploitation, which should be mentioned for completeness, are bistatic operation, where detecting the transmissions does not give us the location of the receiver, or disguising the radar's waveform so that it looks as if its purpose is other than it is. An example of this is the desire to be able to use conventional civil marine radar waveforms for military purposes.

This paper, however, will concentrate on what can be done with the design of the radar itself to minimise its detectability, although the user of such techniques will always be aware of other operational and scenario-dependent approaches which can be used to help achieve the same end.

2. LPI TECHNIQUES

This section and the next compare the relative range at which the radar can detect a given target with that at which a given intercept receiver can detect the radar's transmissions. It will then look at how the radar can design its waveform to minimise the range at which it can be intercepted. Fig. 1 show a sketch of a typical scenario to which this might apply:

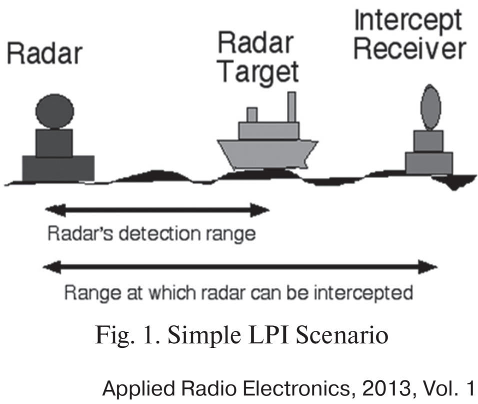

Fig. 1. Simple LPI Scenario

The sensors are assumed to be mounted on ships. One favoured application of LPI techniques, but by no means the only one, is for marine navigation. In a typical tactical scenario the intercept receiver might be carried on the 'target' platform, in which case if the detection range can be made greater than the interception range, the radar will be able 'To See Without Being Seen.'[1] Note that it is not essential to the analysis presented here that the intercept receiver should actually be on the radar target.

This baseline example is also analyzed in reference 2. Reference 3 treats the propagation in more detail, including effects due to multipath and the curvature of the earth, whilst reference 4 considers a number of different scenarios. The latter treats the argument in a slightly different way, so several of its numerical results are slightly different from those presented here, but the principles are the same.

2.1 Interception Range

The basic sensitivity equation for interception of a radar's transmissions is the same as for a simple radio link:

$$SNR = P_p G_t A_r / [4\pi r^2 kTB_i N_i L_i F], \qquad (1)$$

where SNR is the signal to noise ratio seen by the intercept receiver; P_p is the peak transmitted power of the radar; G_t — is the gain of the transmitter (radar) antenna; r — is the range; k — is Boltzmann's constant; T is the temperature of the receivers; N_i is the noise figure of the intercept receiver; B_i is the effective bandwidth of the intercept receiver; L_i represents the losses in the intercept receiver and F is the propagation factor.

The propagation factor is taken to include interference due to multipath reflections, which will usually be predominantly from the earth's surface, as well as factors such as attenuation through clear air and through any precipitation which may be present. For the purposes of this discussion this factor can be ignored and the analysis will look only at the free-space numbers, although, as mentioned above, reference 3 includes a more sophisticated treatment of multipath for one particular scenario.

The product $P_p G_t$ is the peak effective radiated power of the radar and is the basic measure of the power which is available to the intercept receiver when the latter is in the main beam of the radar's antenna.

The peak power is used to calculate the sensitivity of the ESM receiver because it cannot be matched to the waveform of a specific radar for two reasons: if the radar is 'hostile' the intercept receiver will not be able to know its waveforms a priori and, in any case, because it has to be able to detect all the radars in the scenario, its processing cannot be matched to any particular one of them.

The beamwidth of the antenna of the intercept system must also be wide in order to detect signals coming from all directions, and its bandwidth must be wide in order to detect signals at different frequencies. We will see later that all these factors make the ESM receiver much less sensitive than the radar receiver, an inefficiency which, however, in many cases is more than countered by the fact that the propagation to the intercept receiver is only one-way, i.e. there is an r^2 term in the dominator of the equation, unlike the radar case where we will see the familiar r^4 term in the corresponding equation.

In order to reduce the signal to noise ratio which the intercept receiver can obtain against it, or equivalently, to reduce the range at which the intercept receiver can obtain the signal to noise ratio necessary to be able to exploit it, the radar must minimise its effective radiated power and maximize the bandwidth over which the intercept receiver will have to look in order to be sure of intercepting the radar's signals.

2.2 Radar Detection Equation – Mean Power Form

The simplest form of the equation for the radar's detection performance is probably:

$$SNR = P_m G_t^2 \lambda^2 \sigma\tau / [(4\pi)^3 r^4 \times kTN_r L_r], \qquad (2)$$

where P_m is the mean power of the radar; λ is the wavelength; σ is the Radar Cross Section (RCS) of the target; N_r is the noise figure of the radar receiver; L_r represents the losses is the radar receiver and τ is the integration time of the radar receiver.

This form differs slightly from the more familiar form of this equation, in terms of the radar's peak power and the receiver bandwidth, which is introduced as equation (3) below, but brings out more clearly that the sensitivity of the radar is a function of the energy ($P_m\tau$) which it can direct towards the target.

Note that the two receivers are assumed to be at the same temperature.

Apart from the term σ/r^4, the key difference between the two equations is that the mean transmitted power replaces the peak power and the integration time replaces the inverse of the receiver bandwidth. This is because one consequence of the matched filter theorom[5] is that, since the radar knows its own waveform, it can use an optimal receiver which coherently integrates energy over all the frequency components in the signal and yields a sensitivity which is only dependent on the total energy (mean power × integration time) received from the target. As mentioned above, the ESM receiver must be mismatched to the signal and so cannot achieve this gain.

This version of the radar power budget does not include the bandwidth of the signal, because the matched filter in the receiver can coherently integrate all the received power over the whole of the signal bandwidth.

Of course, the radar cannot increase its integration time without limit because this is limited by the rate at which it must be able to deliver information.

The special cases where the intercept receiver can try to approach the processing gain possessed by the radar are discussed briefly in section 6.

The factor $G_t\lambda^2/(4\pi)$ in equation 2 is the effective aperture of the radar antenna, and the equation makes the assumption that the radar's transmit and receive antennas have the same gain - the same antenna would, of course, normally be usually be used for both functions.

The loss term is assumed to include both RF and processing losses. The transmission losses are assumed to be included within P_m, i.e. the latter is assumed to be the power actually radiated from the antenna, because and losses in the transmission feed path will affect the sensitivity of the radar and its ability to be intercepted to the same extent and so it is best to use definitions which avoid the need to consider such losses.

Although the best way to design the radar antenna for LPI is to maximize its gain (strictly, to maximize its receiver aperture) it is also usually desirable to minimise its sidelobes, to inhibit interception of the radar signals when the radar is not actually looking at the intercept receiver. This makes it harder to exploit any interceptions, since they will become intermittent.

2.3 Radar Detection Equation – Peak Power Form

The radar range equation can also, of course, be written in terms of the peak power levels. Although less 'fundamental' than the mean power from, this version is often used and is also closer to the form of the interception equation (equation 1). It takes the form:

$$\mathrm{SNR} = P_p G_t^2 \lambda^2 \sigma G_{PC}/[(4\pi)^3 r^4 \times kTB_r N_r L_r], \qquad (3)$$

where G_{PC} is the processing (pulse compression) gain of the matched receiver and B_r is the effective bandwidth of the radar signal.

This version is more directly comparable with the 'interception' budget in that it includes the peak power and the bandwidth, but the radar still possesses the processing gain of the matched filter, which, by comparison with equation 2, can be seen to be equal to the time-bandwidth product of the signals, i.e. the product of the bandwidth and the integration time. A more detailed analysis of the two forms will show that the processing losses (within the term L_r) are slightly different when using the two models, but these relatively minor differences do not affect the general principles. A concise way of expressing a key LPI design goal, derived from comparing equations 1 and 3, is to maximize the time-bandwidth product of the radar.

3. POWER BUDGETS

3.1. Sensitivity of a typical Intercept Receiver

The sensitivity of ESM receivers is usually quoted in terms of the minimum detectable signal divided by the antenna gain:

$$S = kTB_i N_i L_i . SNR_{min}/G_r, \qquad (4)$$

where SNR_{min} is the minimum signal to noise level required for detection.

This minimum signal to noise ratio is usually controlled in the receiver by dynamically setting the detection threshold this far above the noise floor. This measure is thus related to the power density at the ESM antenna which is necessary to detect the signal. Since the signal level at the receiver input is equal to the power density multiplied by the effective aperture of the antenna, which is equal to $G_r\lambda^2/4\pi$, the minimum power density which can be detected is actually,

$$P_{min} = 4\pi S/\lambda^2. \qquad (5)$$

The detection range deduced from equations (1) and (5) is thus:

$$r_{max} = \sqrt{(P_p G_t/S)}\lambda/(4\pi). \qquad (6)$$

We will now consider a 'classic' case of an Instantaneous Frequency Measurement (IFM) receiver[6]. Although this is no longer the 'state of the art' for receiver sensitivity, it will serve to show how LPI became a 'battle' between the radar and the intercept receiver. Fig. 2 shows a sketch of a block diagram of an IFM receiver.

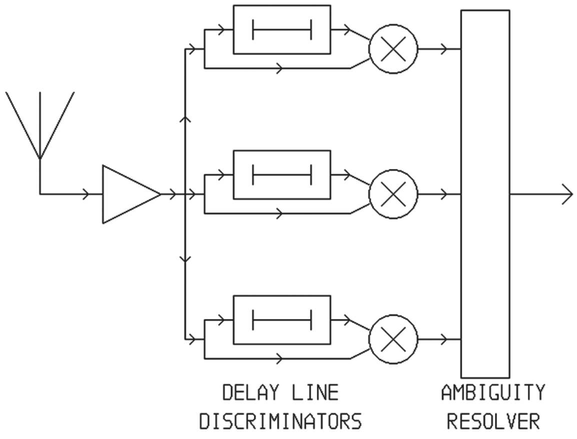

Fig. 2. IFM The Principle of the IFM Receiver

The IFM measures frequency using delay line discriminators. The phase between the direct and delayed paths is a measure of frequency, but is ambiguous as the phase can only be measured modulus 2π. A set of delay lines is therefore used, long ones with a narrow unambiguous range but high resolution and shorter, lower resolution, lines to resolve the ambiguities. The desirable combination of wide frequency coverage and high accuracy is obtained by combining the phase measurements using appropriate logic. Since the set of phase measurements is available from a single pulse, the frequency can be measured within the period of a single pulse, i.e. effectively instantaneously. The noise figure can be defined by the amplifier at the input of the receiver, but the Radio Frequency (RF) bandwidth must be high in order to capture emitters over the whole range of frequencies and will be at least 2GHz. However, the bandwidth after the phase detectors (the video bandwidth) needs only to be fast enough to capture the shortest pulses of interest, and may typically be 10MHz.

This mismatch between the RF and video bandwidths gives the ESM receiver an approximate effective bandwidth of

$$B_{eff} \approx \sqrt{(2 B_{RF} B_v)}, \qquad (7)$$

where B_{RF} is the RF bandwidth and B_v is the video bandwidth.

Using the example bandwidths quoted above the effective bandwidth of the receiver will be 200MHz.

In our baseline scenario, the ESM receiver may be assumed to have an antenna gain of 0dBi, so the aperture will be $\lambda^2/(4\pi)$. In fact the antenna will not be omnidirectional, but it will have a wide field of view, so its directive gain will be low. The need for a wide frequency coverage will add further losses, so the net gain will be close to that of an omnidirectional antenna.

The other parameters of the intercept receiver may be assumed to be:

Table 1

Components of the Sensitivity Calculation for an IFM-based Receiver

Noise Figure:	10 dB
Processing Losses:	4 dB
Minimum Signal-to-noise for detection:	17 dB

Inserting these values into equation 4 gives a sensitivity of -60dBmi.

3.2. Detection range of the baseline radar

We consider first how such a receiver can intercept a ‘typical’ pulse-modulated marine radar. The radar is assumed to have the following key parameters:

Table 2

Parameters of the Pulse Radar

Peak transmitter power:	10 kW
Antenna Gain:	30 dB
Frequency:	9 GHz
(wavelength	3.3 cm)
Pulse Width:	100 ns
(Receiver Bandwidth:	10 MHz)
Noise Figure	4 dB
Losses	4 dB
Pulse Repetition Frequency:	1 kHz
Azimuth beamwidth:	1.2°
Scan rate:	40 r.p.m.
(Dwell Time	5 ms)

The wavelength, the receiver bandwidth and the dwell time are in brackets because they are derived parameters.

The radar’s receiver bandwidth has been taken to be approximately the reciprocal of the pulse length. The radar is has a lower system noise figure than the intercept receiver because it has a narrower bandwidth and is generally better ‘tuned’ to its signals.

The dwell of 5ms allows five pulse to be integrated across the beam. This is assumed to lead to an incoherent gain of 4dB, which lowers the effective bandwidth to 4MHz. Putting these figures into equation 3 show that the radar can detect a target with an RCS of 100m^2 (such as a small ship) at a free-space range of 20km. with 15dB signal to noise ratio.

3.3. Baseline Intercept Range

Inserting the parameters of the pulse radar into equation 5 gives an intercept range of 250km, i.e. more than an order of magnitude greater than the range at which the radar can detect its target.

3.4. LPI Radar Intercept Range

If we follow the principle outlined above and change the radar design to increase the duty cycle to 100% this will allow us to reduce the peak power from 10kW to 1W without changing the mean power and hence without changing the detection performance, so the radar will still be able to detect the ship at 25km range.

The radar can be assumed, for convenience, to use Frequency-Modulated Continuous Wave (FMCW) modulation, although this is not critical to these high-level sensitivity calculations. The full set of parameters of the this radar are listed in table 3 for convenience:

Table 3

Parameters of the FMCW Radar

Mean transmitter power:	1W
Antenna Gain:	30dB
Frequency:	9GHz
(wavelength	3.3cm)
[Sweep Bandwidth	10MHz]
Noise Figure	4dB
Losses	4dB
Sweep Repetition Frequency:	1kHz
(Coherent Integration Time	1ms)
Azimuth beamwidth:	1.2°
Scan rate:	40 r.p.m.
(Dwell Time	5ms)

As in table 2, the wavelength and the dwell time are in brackets because they are derived parameters. The coherent integration time is also in brackets because it is derived from the sweep repetition frequency. The sweep bandwidth is in square brackets because it is not used in the calculations in this section of the paper.

Five sweeps can be integrated incoherently over the dwell, in a process analogous to the incoherent integration of the pulses for the pulse radar. The detection range can be calculated using either equation 3 or, more conveniently, using equation 2 and will, of course, be the same as that of the pulse radar. Although there may be practical difficulties in achieving this performance with some CW radar designs, it has been shown[2,3] that an FMCW radar can achieve this performance and this may also be possible in the future for with radars using noise waveforms for example.

Although it has no effect on the sensitivity of the radar, the change in modulation has a dramatic effect on the range at which its transmissions can be intercepted. The reduction in peak power from 10kW to 1W means that the intercept range is reduced by a factor of 100 to only 2.5km, i.e. the LPI radar can indeed detect its targets at much greater ranges than those at which its own transmissions can be intercepted.

The general principle of minimizing the probability of intercept is therefore to spread the radar signal as widely in time and frequency as possible in order to minimise the power density at the intercept receiver. It is also, of course, valuable to maximize the uncertainty of its bearing, to prevent the intercept receiver from using a directional antenna, with a relatively large receiver aperture, which would increase the receiver’s sensitivity.

4. NARROW-BAND INTERCEPT RECEIVERS

It will be appreciated that the sensitivity of the intercept receiver has been severely limited by making it ‘wide open’ in frequency and bearing. This is needed in order to retain a high ‘Probability of Intercept’ so that the receiver can be sure of rapidly detecting all the signals which are in the environment. However, in some cases it might be worth trying to increase the sensitivity, i.e. increase the intercept range, even if the probability of being able to intercept the signal over any given time period has to be reduced as a result.

4.1. Superheterodyne receiver

As an example of a receiver which trades probability of intercept for sensitivity is the superheterodyne (superhet) receiver. This uses a relatively narrow band receiver which is swept in frequency to look for the radar. A typical superhet might have a bandwidth of 2MHz, giving it 20dB better sensitivity than our IFM. This would mean that the free-space range at which our LPI radar could be intercepted would be increased by an order or magnitude, to 25km, i.e. to a value which is very similar to the range at which the radar can detect its target. If the superhet is to dwell for long enough to be able to characterize the radar, however, i.e. for several milliseconds, it will now take several seconds to cover the bandwidth of 2GHz which our IFM could cover instantaneously. A faster scan could cover the band much more quickly, but the shorter ‘dwell’ on each frequency would not allow the signals to be characterized, i.e. we would be trading ‘Probability of Intercept’ against ‘Probability of Exploitation’ as well as trading both against intercept range.

If the radar is agile from sweep to sweep within the dwell, or if it is agile from scan to scan but the intercept receiver cannot cover the whole of its agile band within a single dwell, then the interception of the radar’s signals become a probabilistic process. The process of intercepting the radar in this case can be modelled by a Poisson distribution, for which the probability of failing to make an interception is

$$(1 - p_i) = e^{-n\psi} \tag{8}$$

therefore

$$p_i = 1 - e^{-n\psi}, \tag{9}$$

where p_i is the probability of intercepting the radar, n is the number of opportunities for interception and ψ is the probability of interception on one opportunity. For example if the superhet dwelt for 1ms, its probability of being on the right frequency to intercept the radar at some time within its dwell would be approximately the ratio between the bandwidth of the radar signals (10MHz) and the superhet’s search bandwodth (2GHz) i.e. about 0.005, whereas if it dwelt for only 10μs it would cover about a hundred 10MHz-wide ‘windows’ during the radar’s sweep time, so the probability of intercept would become $1\text{-}e^{-0.5} \approx 0.4$.

There is a steep trade-off between detection probability and sensitivity. The general shape of this trade-off is shown in fig. 3.

The effect of an increase in intercept time is multiplied because if the receiver can only intercept the radar’s main beam, then if it cannot detect the radar during the 5ms for which the radar is illuminating it, it will not have another chance to do so until the next scan, 1.5 seconds later.

The two cases shown in figure 3, for 90% and 10% cumulative PoI illustrate the times until the interceptor can be reasonably sure of finding the radar, and that for which the radar can be reasonably sure that it has not been detected. The separation between these lines (approximately a factor of 20 in time) highlights the important tactical difference which can arise as a consequence of deciding which criterion is appropriate in a particular scenario.

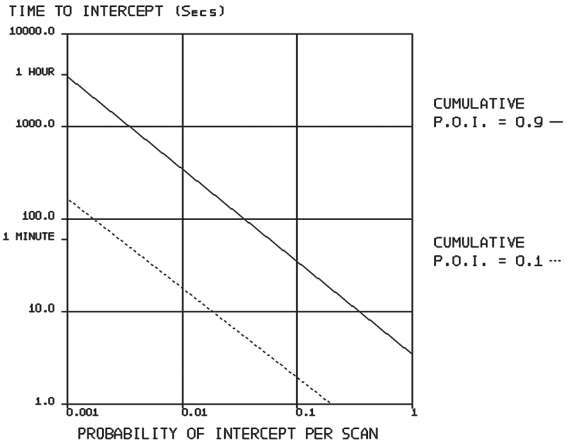

Fig. 3. Effect of Probability of Intercept on Time to Intercept the Radar

4.2. Channelized Receivers

The ideal is, of course, to obtain the sensitivity of a narrow-band receiver with the probability of intercept of a wide-open receiver. The only known way to do this is to create a series of receivers in parallel. Figure 4 shows an outline sketch of a channelized receiver architecture.

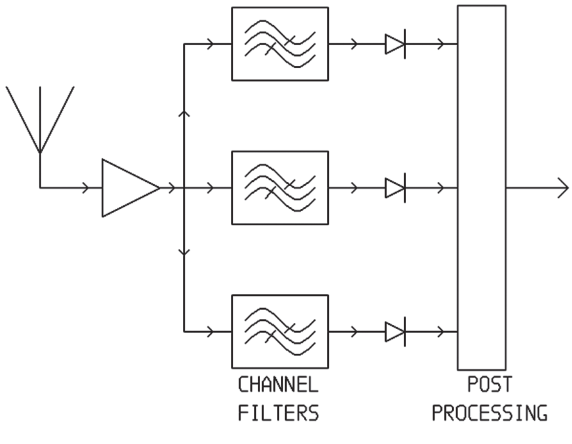

Fig. 4. Outline of a Channelized Receiver

Each ‘channel’ is a narrowband receiver, with the sensitivity appropriate to such a receiver, but the multiplicity of such channels in parallel give the coverage of a ‘wide open’ receiver. Non-trivial logic is required after detection to ‘pull together’ all the information on the scenario and to suppress potential artifacts such as those which can occur when signals straddle several channels. This sort of architecture has been popular since the late 1980’s where high sensitivity and wide bandwidth are required simultaneously. Some of the early implementations used analogue filters, but modern implementations predominantly used Fourier transform based techniques to create the required parallel channels. Such a receiver would typically have a channel bandwidth, and hence a sensitivity and interception range, equal to that of the superhet, but with 100% probability of intercept against the main beam of the radar.

As well as providing better sensitivity, the channelized receiver also allows multiple signals on different frequencies to be seen simultaneously. This was difficult with an IFM, but it has become more necessary as the duty cycles of conventional radars have increased, so that it is now quite likely that signals from several radars will be present simultaneously in the receiver.

5. INTERCEPT RECEIVER PROCESSING GAIN

It was mentioned in section 3 that a general-purpose intercept receiver will not have any processing gain against the radar signals because it does not know *a priori* what processing it should apply. Various attempts, have, however, been made to overcome this limitation. Attempts have been made to obtain coherent processing gain against LPI radars, but these generally fail either if the signal to noise ratio is low (which is just when the gain is needed), because the signals are then too corrupted by noise, or else they are too vulnerable to relatively minor changes in the radar waveform.

Other approaches have used non-linear processing, but this is easily upset when multiple signals are present. This is a problem since the LPI signals will be the weakest of those present and hence the ones most likely to be lost amongst any spurious signals introduced by the processing.

The relative failure of attempts to create intercept receivers using coherent processing has led instead to the idea that one should try to do as well as one could to match the receiver to the bandwidth and duration of the signal being intercepted, but without attempting any coherent processing of it. This is the idea behind the Matched Incoherent Receiver (MIR). This is a radiometric receiver, i.e. it attempts only to detect the presence of RF energy but not its characteristics. It is designed with an RF bandwidth equal to the radar's agile bandwidth and a video bandwidth equal to the reciprocal of its dwell time. Although the details of such a receiver become specific to the particular radar, the rule can be applied to the detection of any radar waveform. It probably represents the 'worst case' intercept scheme against the radar and although such a receiver is unlikely to exist for any particular radar, it represents a good baseline against which the practical robustness of a radar's the LPI performance can be assessed.

The name 'Matched Incoherent Receiver' is therefore used for this receiver because it is matched both to the RF bandwidth of the signals to their information bandwidth, but not to the details of the waveform. Its use would mean that the radar would no longer have the advantage of a mismatch between its bandwidths and those of the intercept receiver, but only the advantage of knowing its own waveforms. This principle allows the intercept receiver to recover the square root of the radar's time-bandwidth product, and it is, of course, the time bandwidth product which gives the radar its LPI characteristics. Shirman et al.[7] have also reported that the performance of this receiver is very insensitive to errors in the estimates of the time and bandwidth of the signals.

To detect the FMCW radar described in section 3.3 and in table 3, for example, the MIR would have an effective bandwidth of 200kHz, making it 30dB more sensitive than our baseline IFM-based receiver, giving it a free-space detection range of about 80km against the main beam of our 'LPI' radar design.

5.1 Trade-off between sensitivity and information

It is noteworthy that in order to maximize its sensitivity as a detector, this radiometric receiver destroys all the information about the signal. There is an interesting analogy between this behaviour and the true, coherent, matched filter[5]. In the latter case, the matched filter has a frequency response which is the complex conjugate of the spectrum of the signal, so the filtering process removes all the phase information from the signal and hence destroys the information about the 'shape' of the signal in the time domain.

It is speculated that an efficient detector, by 'gathering together' as much as possible of the energy in the signal will always tend to destroy the information which an intercept receiver might otherwise want to retain in order to identify it.

6. NOISE WAVEFORMS FOR LPI

The design principle of the Matched Incoherent Receiver implies that the LPI performance is independent of the details of the waveform, being driven entirely by its overall integration time and its overall bandwidth. From that point of view, noise waveforms would be expected to have the same LPI characteristics as other CW waveforms such as FMCW.

6.1. Security from Potential Interception Strategies

There are, however, two other benefits of using random waveforms. The first of these comes from the consideration that it may in fact be possible to design practical receivers for deterministic high-duty-cycle waveforms which can exploit their deterministic properties, even though, as was argued in the previous section, no practical scheme for doing this has yet been implemented. No such improvement in sensitivity over the radiometric receiver is possible, against noise, however, unless the particular noise sequence is known, and this is not possible if the sequence is generated at random in real time. The use of random waveforms thus gives protection against any exploitation of the characteristics of the signal which might become possible in the future.

6.2. Security from Range-Gate Pull-Off Jamming

The other advantage possessed by a noise waveform is that it will defeat the attempt to use a Digital Radio Frequency Memory (DRFM) to achieve range-gate pull-off.

The significance of range-gate pull off as a jamming technique, and the way in which increasingly more sophisticated jamming and counter-jamming techniques have developed over successive generations of equipment is in itself a very good example of the continuing 'battle' between radar and electronic countermeasures systems, as well as being of practical relevance for noise radar in particular.

Range-gate pull-off relies on placing a false target close to the return from the real target, and persuading the radar to track the false target instead of the real one. As illustrated in figure 5, older jammers could place the false target behind the real one, by re-transmitting the signal received at the target.

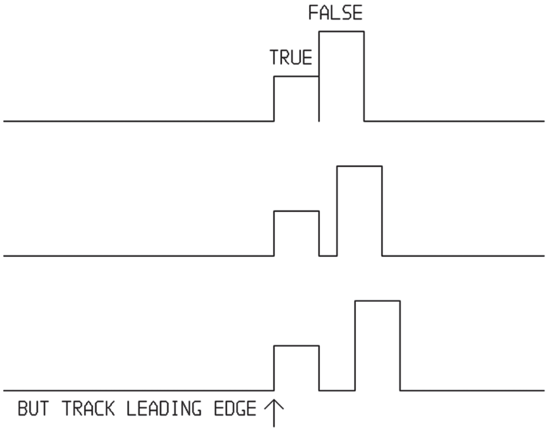

Fig. 5. Principle of Range-Gate Pull-Off

The plots illustrate three successive 'A-scope' images showing the 'true' signal reflected from the target and the 'false' signal re-transmitted by the jammer.

The false target is bigger than the real one and is slowly moved away from the real one by increasing the delay before retransmission. When the two signals are well enough separated, the false target is removed, leaving the radar with nothing to track.

As noted in the text of the lowest 'A scope,' however, a newer generation of radars countered this technique by tracking the 'leading edge' return. This would, of course, ignore a false target behind the true one and this was done specifically to defeat range-gate pull off.

If the jammer is on the platform to be protected, as is frequently the case, the principle of causality prevents it from creating a false copy of the true signal which can reach the radar before the 'true' return, so the next step in the battle has been to 'counter' the leading edge tracker by exploiting the repetitive nature of the radar signals and delay the received signal by slightly less than the pulse repetition interval (or equivalently, the sweep repetition interval for an FMCW radar) so that the false signal appears slightly before the true reflected signal from the next pulse as illustrated in fig. 6.

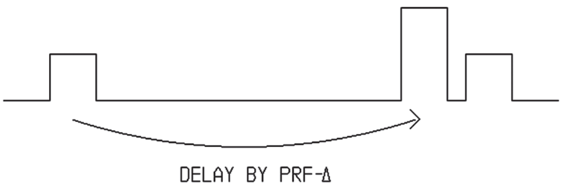

Fig. 6. Principle of a DRFM - Used to Create An Up-Range False Target

The 'leading-edge' tracker will then still be deceived into following the false signal. This does not work against a noise waveform however, because the signal is non-repetitive, and non-deterministic, so delaying the signal can never be equivalent to moving the signal 'forward' in time.

It is worth remarking about this is not an 'LPI' feature so much as a way of preventing exploitation of the radar. This can be illustrated by considering the fact that the repeater jammer can in principle jam the radar with false targets without being able to detect the signals . It can repeat a signal which is buried within the jammer's own receiver noise and rely on the radar which is being jammed to use its own signal processing gain to extract the false signal from the noise. - Of course it would need information from somewhere, possibly from the known characteristics of the signal, in order to know the repetition period.

It is important to note that these strengths are based on the unpredictability of the signals and, at least in principle, they will be compromised if pseudo-noise waveforms, using pseudo-random sequences or the outputs of chaotic systems, are employed instead of pure noise, although their practical exploitation would still be very difficult

CONCLUSION

This paper has illustrated how an intercept receiver can easily detect the signals from a conventional radar at long range, even though its receivers are relatively insensitive due to the need for them to be wide open in both frequency and bearing, because the intercept path uses only one-way propagation (r^2) whereas the radar's detection of its targets requires two way (r^4) propagation.

LPI radars can overcome the effect of this r^4 path loss by using high processing gains which the intercept receiver cannot match. The current interest in LPI techniques and methods of countering them has arisen since modern radar hardware has made it practical to use waveforms with very high time-bandwidth products.

Classical intercept receiver designs can only overcome the radar's processing gain at the expense of a reduced probability of intercepting the radar, which may make them tactically ineffective.

More sophisticated channelized receivers, or special-purpose 'matched incoherent receivers' can recover most of the intercept receiver's range advantage. It should be noted however, that this is only the case when the main beam of the radar points at the intercept receiver. Achieving high intercept ranges is still difficult against the radar's sidelobes. The issues associated with this go beyond what can be discussed in this paper, but are considered in reference 4.

Noise radars have a theoretical immunity to 'clever' interception schemes, and a practical immunity to up-range false target jamming, but these benefits may be compromised if pseudo-random waveforms are used, rather than those which are truly random.

Low Probability of Intercept can be a genuine and important feature of a radar, but its significance is scenario dependent.

The ‘battle’ between designing radars to exploit increasingly-sophisticated waveforms and intercept receivers of increasing sensitivity and sophistication has been played out over many decades in the past and will doubtless continue into the future.

References

[1] Fuller, K. L., ‘To See and Not be Seen,’ Proc. IEE **137**, Pt F., pp1-9, (1) February 1990.

[2] Stove, A. G., Beasley, P. D. L., Reits, B. J. and Ås, B-O, ‘Das PILOT-Radar,’ Proceedings of MIOP ‘90, Stuttgart, 1990.

[3] Ås, B.-O., ‘The PILOT, A Quiet Naval Tactical Radar,’ proceedings of Radarcon 90, Adelaide, 1990, pp. 165-71, published by DSTO.

[4] Stove, A. G., Hume, A. L. and Baker, C. J., ‘Low Probability of Intercept Radar Strategies,’ IEE Proc. Radar Sonar & Navig, 151 (5), pp249-60, October 2004

[5] Cook, C. E. and Bernfeld, M., ‘Radar Signals,- an Introduction to Theory and Application,’ New York, 1967, Academic Press, Library of Congress Catalog 66-30803, Chapter 2

[6] East, P. W., ‘Fifty Years of Instantaneous Frequency Measurement,’ IET Proc. Radar Sonar & Navig. **6**, pp112-122, (2) February 2012

[7] Y. D. Shirman, V. M. Orlenko and S. V. Seleznev, “Passive Detection of Stealth Signals,” Proceedings of European Radar Conference 2004, pp. 321-4, October 2004

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Радары с низкой вероятностью обнаружения / А.Г. Стоув // Прикладная радиоэлектроника: науч.-техн. журнал. – 2013. – Том 12. – № 1. – С. 114–121.

Появление широкополосных радаров с большими относительными длительностями включения привело к тому, что стало практичным создавать радары с коэффициентом усиления обработки достаточно высоким для работы на дальностях, на которых сигналы этих радаров не могут быть перехвачены. Данная работа рассматривает принципы таких радаров с низкой вероятностью перехвата и иллюстрирует их простыми количественными примерами, сравнивая характеристики с импульсными радарами с линейной частотной модуляцией сигналов. В качестве базы в данной работе рассматривается приемник с использованием техники измерения моментальной частоты, но обсуждаются и другие возможные варианты радаров, и исследуется противоречие между чувствительностью перехвата и временем перехвата. Приводятся аргументы в пользу того, что согласованная фильтрация – не лучший способ перехвата радара с низкой вероятностью перехвата. Рассматриваются достоинства согласованного некогерентного приемника, где время предетектирования и ширина полосы пост-детектирования согласованы с радиолокационным сигналом, но обнаружение некогерентно. Кроме того, обсуждаются дополнительные достоинства в этой сфере, потенциально доступные для шумовых радаров. Подчеркнута важность в военном сценарии низкой вероятности перехвата и, в частности, дополнительного принципа низкой вероятности использования сигнала.

Ключевые слова: низкая вероятность обнаружения, приемник-перехватчик, радиоперехват.

Ил. 6. Библиогр.: 7 назв.

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Поява широкосмугових радарів з великою відносною тривалістю включення призвела до того, що стало практичним створювати радари з коефіцієнтом посилення обробки достатньо високим для огляду відстаней, на яких сигнали цих радарів не можуть бути перехоплені. Дана робота розглядає принципи таких радарів з низькою ймовірністю перехоплення та ілюструє їх простими кількісними прикладами, порівнюючи характеристики з імпульсними радарами з лінійною частотною модуляцією сигналів. Як база у даній роботі розглядається приймач з використанням техніки вимірювання моментальної частоти, але обговорюються й інші можливі варіанти радарів, досліджується протиріччя між чутливістю перехоплення і часом перехоплення. Наводяться аргументи на користь того, що узгоджена фільтрація — не кращий спосіб перехоплення радара з низькою ймовірністю перехоплення. Розглядаються переваги узгодженого некогерентного приймача, де час попереднього детектування і ширина смуги пост-детектування узгоджені з радіолокаційним сигналом, але детектування є некогерентним. Крім того, обговорюються додаткові переваги в цій сфері, потенційно доступні для шумових радарів. Підкреслено важливість у військовому сценарії низької ймовірності перехоплення і, зокрема, додаткового принципу низької ймовірності використання сигналу.

Ключові слова: мала імовірність детектування, приймач-перехоплювач, радіоперехоплювання.

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