Radar And ESM: The Current State Of The LPI Battle

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Abstract

This paper discusses the current and projected future capabilities of "Low Probability of Intercept" radars and of the intercept receivers used by Electronic Support Measures (ESM) systems. In discussing the possible future sensitivity of the latter it makes use of the Matched Incoherent Receiver to show how the intercept ranges may be able to increase in the future. It then discusses future radar tactics which can make interception harder, and concludes that there is no overwhelming advantage to one side or the other, but the balance will depend on the particular tactical situation.

Keywords: Radar, Electronic Support Measures, Detectability, Low Probability of Intercept

Introduction

The "classic" situation between radar and ESM (intercept receivers) has been that the intercept receiver has no difficulty detecting the radar, and even sometimes its sidelobes, at long ranges. This is because the radar must transmit enough power for the signals to be detectable even after reflection at the target, whereas the propagation between radar and ESM is only one-way.

More recently, however, the increased signal processing gain obtainable from a radar. which is often expressed in terms of the time-bandwidth product of the signals being processed, has given the radar the potential ability to alter that balance, on the assumption that the intercept receiver cannot duplicate the radar's processing gain.

This paper discusses some of the issues which arise from this situation. These issues have been studied in the EMRS-DTC project on "Robustness of Low Probability of Exploitation." Although some of them have been considered before within both the radar and Electronic Warfare communities, the systematic, integrated, analysis, giving equal weight to the potential developments on both "sides" has not previously been addressed.

Interception and Exploitation

Another measure of the difficulty of intercepting or identifying the radar power it transmits, since conventional intercept receivers are generally sensitive to the peak power in the signal, whereas the radar, using a matched filter, is sensitive to mean power. "Low Probability of Intercept" is the usual term to describe radars which pose difficulties to an ESM system because of the weak signal levels which it presents to the receiver, and generally refers to signals which are difficult to detect above the ESM receiver's threshold. A more operationally-meaningful measure is the ability of the intercept receiver to react to the detection of the emitter. Recognition of this need for the "interception" to lead to "exploitation" of the intercept has lead to the use of "Low Probability of Exploitation." Exploitation generally requires measuring some of the parameters of the signal. Radars which are hard to detect are generally also hard to "exploit" (Stove et. al.(1)), although other complex waveforms, for example waveforms which are variable in frequency or in their pulse parameters, may also be hard for ESM systems to identify and exploit, even though they may be high power and hence not hard to intercept.

Intercept Ranges

Although a variety of radars exist with low peak power levels, and some have well-established LPI/LPE characteristics, the radar family which has made the greatest play of its LPI/LPE capability is PILOT/SCOUT (Ås (2)). A good place to start the analysis of the issues is with a baseline performance of this radar against a typical late-1980's IFM-based ESM. The following tables, which are also given in reference (1), indicate how the range at which the radar can detect its target and at which it can be detected, in free space, can be calculated:

Mean transmitter power	1W
Antenna Gain	30dB
(Effective Radiated Power (ERP)	60dBmi)
Frequency	9GHz
Integration time (1kHz bandwidth)	1ms
Target RCS	100m^2
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Received Power at 20km range	-125dBm
Noise Figure	4dB
Noise Floor	-144dBm
Incoherent Integration Gain	4dB
Losses	4dB
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Signal to Noise Ratio	15dB
Agile Bandwidth	100MHz

Table 1: Performance of the Baseline Radar

ESM Receiver Antenna Gain	0dB
IF Bandwidth	2GHz
Video Bandwidth	10MHz
Effective Bandwidth	200MHz
Noise Figure	10dB
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Noise Floor	80dBmi
Processing Losses	4dB
Minimum Signal/Noise for detection	17dB
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Net sensitivity	-60dBmi
Incident power density from 60dBmi at 2.5km	-19dBm/m2
Effective Aperture	-41dBm^2
Received Power at 2.5km	-60dBm

Table 2: Performance of the Baseline ESM System

These tables show that the radar can detect its target at 20km range, whilst its emissions can only be intercepted at 2.5km range, which confirms that, at least in this scenario, the radar is "tactically indetectable." Its conclusions have also been given, for example, in reference (2) .

The need for the current study clearly arises from the fact that the design of both the radars and the ESMs, and the ways in which they can be used, have moved on since the PILOT radar was first launched in 1989. It may be argued that some of the developments in ESM since that time have been at least encouraged by the existence of LPI radars, and the more detailed consideration of how an LPI radar can be used, and how it can be made more robust against interception by more sophisticated receivers has been inspired by the obvious simplicity of the analysis behind the "headline" comparison - it inevitably invites the asking of a lot of more sophisticated questions.

The Matched Incoherent Receiver

There are a lot of intercept receiver designs which have been, are being, or might be used to detect a radar, but the key measures of significance for comparing their performance in simply detecting relatively weak emitters is:

- the combination of pre- and post-detection bandwidths and
- their antenna apertures.

Parameters such as noise figure and threshold-to-noise ratios are of course also important, but they are less "interesting" since they tend to be quite similar over a wide range of receivers.

A benchmark for comparing the sensitivities of the receiver is the "Matched Incoherent Receiver," (MIR) the architecture of which is shown below:

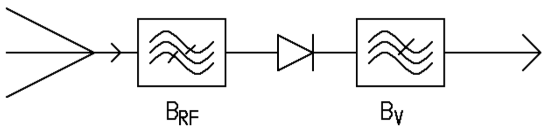

Figure 1: Block Diagram of the Matched Incoherent Receiver

In this hypothetical receiver, the front end amplifier defines the noise figure. The RF bandwidth of the receiver is matched to the RF bandwidth of the signal and the post-detection video bandwidth is matched to the dwell time of the signal. If the signal is agile but with a narrower instantaneous bandwidth, the RF bandwidth of the intercept receiver is assumed to be matched to the agile bandwidth. The MIR is not a good practical receiver, but it has no measurement capability and hence no ability to distinguish one emitter from another, it establishes a useful baseline for the sensitivity which might be expected from a near-ideal ESM receiver because its bandwidths are matched as well as they can be to the signal, but uses incoherent, rather than coherent, integration since it has no detailed knowledge of the waveforms being used by the radar.

The MIR forms a useful generic starting point for the analysis of future ESM capabilities because it does not require a detailed knowledge of the receiver architectures, but can treat them at a more general level. For example, it is shown in reference 1 that the MIR provides a good estimate of the best-case sensitivity which a scanning superhet. can achieve against an agile modulated-CW emitter.

The sensitivity of the MIR is approximately $\sqrt{(2B_{RF}B_V)}$, so for a radar with 100MHz bandwidth and 4ms dwell time (a bandwidth of 125Hz), the effective bandwidth is about 160kHz, compared with 2GHz for the IFM-based receiver discussed in table, and is indicative of the practical limits of sensitivity of the intercept receiver.

This is about 20dB better than a current "state of the art" channelized receiver and would allow the free-space interception range to be increased to 280km against the main beam of the "baseline" radar whose parameters are shown in table 1, but the range against sidelobes 40dB below the main beam would still be only 2.5km and the range would only be 8km if the transmitter power could be reduced to 1mW. Obviously, other variations of these figures are possible.

Intercept Time versus Receiver Sensitivity

If the sensitivity of the MIR is to be achieved with a general-purpose ESM, then either a very high degree of channelization would be required, or a relatively low probability of intercept would have to be tolerated. The sensitivity could be increased further by using larger antenna apertures, but there two limitations to this. One is the limit of the maximum antenna size which the user, or his platform, will tolerate and the second is that unless yet more channelization is used, the reduced beamwidths of the larger antennas will also act to reduce the probability of intercept. It cane be seen that as well as the “scientific” limit to the detectability of signals, there are also “economic” limits beyond which the increased cost and complexity of the ESM would not be considered worthwhile.

Receiver Developments

It is interesting to note that whilst PILOT has been in service for about 15 years, the raw sensitivity of ESMs is only at the level which was considered to be the “state of the art” in development when the radar was introduced, so the radar's LPI has proved, form the radar designer's point of view, to be encouragingly robust' over a reasonable time period. The rate of development of both radar and ESM systems has proved to be significantly slower than might have been expected 15 years ago. This has been in part a consequence of the end of the cold war which removed the most electronically-sophisticated “threats” and in part an example of the general slowing-down of advances in electronics as the field matures.

The developments which have occurred over the last decade are

- it has become practical to use channelization to reduce the noise bandwidth of the receiver, whilst retaining the coverage.
- besides improving the sensitivity, channelization also allows the receiver to cope with multiple simultaneous signals and
- advanced Pulse Train Analysers have begun to be used in practical equipment. These analysers are well able to cope with current radar waveforms and the developers are confident that they will be able to cope with future emitters.

The current state of the art receivers have detection systems which are about 20dB more sensitive than the baseband design discussed in the preceding section. This would increase the range at which the radar can be detected to about 25km, which is comparable with the range at which it can detect a target with a radar cross section of 100 square metres. As predicted in reference (2), the effects of the earth's curvature means that the range at which the radar can detect its targets and the range at which its emissions can be detected become the same. This means, in practice, that a user cannot blithely assume that the radar will not be detected. If care is taken in the use of the radar, however, by transmitting only the minimum power required to perform its job, and especially minimising the power emitter in the direction of possible ESMs, the user of the ESM certainly cannot be sure that he will then be able to detect the radar efficiently.

The improved sensitivity will allows the main beam of the radar to be detected at longer ranges - often to the horizon when both radar and ESM are on the surface, but will not give the sensitivity to intercept the main beam significantly beyond the horizon, nor to intercept the sidelobes at long range.

One potential future development of ESM receivers is digital channelization, using a fast Analogue to Digital Converter and a Fourier-Transform-based filter bank. This does not in itself improve the sensitivity or help the analysis, but will probably make the channelizer more affordable.

Coherent Integration by the ESM

An apparently-radical improvement to the performance of the intercept recover would be if they could use coherent integration which would nullify the radar's processing advantage. This requires a correct "guess" at the waveform out of a large number of possibilities. Note that since the intercept receiver already has a gain of $\sqrt{TB}$ from incoherent processing, compared with a gain of TB for coherent integration, where TB is the time-bandwidth product of the signal. This means that if the parameters of the signal cannot be estimated to an accuracy of better than $\sqrt{TB}$, the coherent integration will actually be less effective than incoherent integration. For example if the time bandwidth product of the signal is 40dB, the waveform would have to be estimated to better than 1% for coherent integration is to be more effective than incoherent integration. In order to achieve the same gain as the radar, the intercept receiver will have to estimate the radar parameters to a precision of 0.01% before detection is achieved.

Future Radar Developments

The previous discussion has emphasised that the radar most integrate its signals coherently if it is to retain a robust LPI performance. It must also spread its energy over a wide bandwidth, and the importance of frequency agility for robust LPI performance is becoming better appreciated. PRI agility is also desirable, but is generally not possible for a general pulse-Doppler radar, although it can be done for some special cases of coherent single-target tracking (Pribić (3)).

Omnidirectional transmission can sometimes be more covert than directional signals, since the integration times can be increased still further, increasing the "dwell time" until it equals the "scan period." This can also be understood as distributing the signals over space as well as time. This approach also removes the information needed by some non-cooperative bistatic receivers to "hitchhike" on the transmissions.

Noise Waveforms

There is a commonly-held belief that LPI radars will, in future, have to transmit more noise-like waveforms than have commonly been used in the past, in order to avoid being intercepted, but the arguments above about the precision with which even a deterministic waveform would have to e be estimated in order to be integrated coherently, combined with the gain which can be achieved with incoherent integration, together with the practical difficulty of implementing more noise-like waveforms may significantly reduce the attractiveness of this idea.

Omni-Direction Transmitters and Bistatic Operation

As discussed in reference (1), if an omnidirectional antenna is used for transmission, then a multi-beam antenna system, for example using a digital beamformer, is required in order to retain the system's sensitivity and directivity. This receiver is also ideally suited to "pulse chase" as a bistatic receiver. Bistatic operation can offer the ultimate in "Low Probability of Interception" for a short-range tactical radar if this is implemented with a close-in bistatic receiver with the targets being illuminated by a long-range, stand-off emitter.

As well as the technical and economic factors which influence the practical use of LPI radars on the battlefield, there are also geographic and tactical limitations. The influence of the horizon has already been mentioned. A number of ways of using the current and future technologies are listed below, but the decision as to which will be significant will depend of the particular application. These are:

- Switching between omnidirectional or directional transmissions depending on whether or not it is likely that, in the latter case, illumination of the intercept receiver by the radar's main beam can be avoided, since the sidelobes of a directional transmitter will generally be lower than the gain of the omni-directional antenna.

- Using the radar as a bistatic receiver and as a short-range active radar only to cover regions which are not illuminated by the transmitter.

- Controlling the radar power to avoid emitting more power than is required - for example reducing the power if the ability to "burn through" bad weather is not required at a particular moment, or if the detection range will in any case be limited by the terrain.

Conclusion

An earlier paper (Fuller (4)) compared the battle between radar and ESM to the Trojan war. A more appropriate analogy now might be a game of chess, in which each side has the same number of pieces, but the victory will go to the player who uses skill and intelligence to make the best tactical and strategic use of the assets at his disposal. Or to revert to the image of the Trojan war, Wily Odysseus in the end was more effective than the Wrath of Achilles.

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