DETECTION LPI RADAR

ABSTRACT

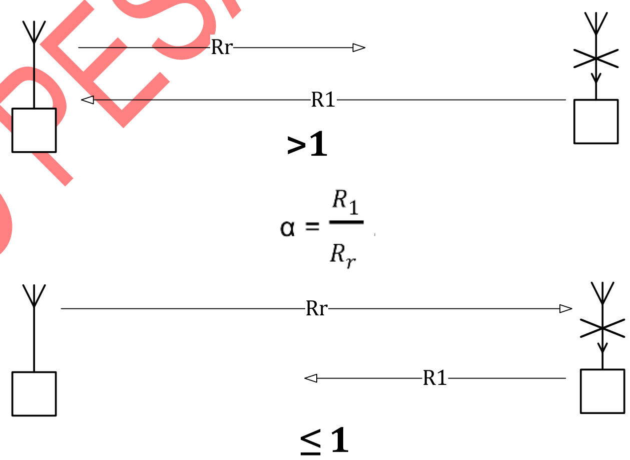
The increase in low-probability radars integrated into modern naval platforms, air defence systems, anti-ship missile type weapons, and littoral weapon systems has led to the development of new technologies, strategies and equipment; how to develop methods and means to counter LPI radar threats embedded in modern platforms and weapons and focus on related techniques, strategies and technologies.

Background

Most of the ES (Electronic Support) interception and EA (Electronic Attack) disturbance systems have to face capable and technologically advanced threats on the battlefield; they must therefore be designed to contribute to the degradation of these systems, to reduce the performance of the radar via the noise.

Radars to survive these countermeasures and carry out their mission, must "hide" their emissions from hostile receivers. To achieve this and mask their presence, radars use power management, wide operational bandwidth, frequency agility, suppression or reduction of secondary lobes and advanced scan patterns (Modulations). These radars are called Low Probability of Intercept (LPI) radars and use the technique "to see without being heard".

Many receivers that use conventional interception techniques do not intercept and identify LPI radars. Mismatched waveforms used by LPI radars cause ESM or RWR systems to have difficulty detecting the presence of the radar or even detecting it at a distance below the range advantage factor. The ESM system detects the LPI radar when it is almost within line of sight. A lethal disadvantage for naval or aerial platforms.



The detection of Radar Rr should be longer than that of intercept receiver R1 . A range factor α can be defined as Range Advance Factor (RAF) α = . If α >1, the radar will be detected by the intercept receive, On the other hand, if α ≤ 1 the radar can detect the platform while the intercept receiver platform can not detect the radar, in fact, so called LPI performance is a probable event.

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LOW PROBABILITY OF INTERCEPT RADAR (LPI)

LPI Radar Principles

In the modern battlefield, the most dangerous threats to a radar come from electronic attacks (EA) and ARM (Anti Radiation Missile) missiles. An essential requirement for modern radar systems is the ability to see and not be heard; the LPI technique has enormous potential for detaining targets without being heard.In order to hide from the interception of ES systems ad RWRs, the detection range of radar R_r should be longer than that of intercept receiver R_1 . A range factor α can be defined as Range Advance Factor (RAF) $\alpha = \frac{R_1}{R_r}$. If α >1, the radar will be detected by the intercept receive, On the other hand, if α ≤ 1 the radar can detect the platform while the intercept receiver platform can not detect the radar, in fact, so called LPI performance is a probable event.

LPI technique

A number of steps can be taken to make a radar less susceptible to detection. One is to make the signal so weak that the ESM signal cannot receive it. This is difficult for radar because the radar must receive enough energy after a round-trip to the target (40 log interval in the radar range equation) to detect the target. The receiver only encounters a one-way path loss (20 log intervals).

A second way is to narrow the radar beam (thus increasing the antenna gain) or to suppress the antenna sidelobes. This makes it more difficult for a receiver not positioned on the target to intercept the signal but has no impact on a receiver located on the target.

A third way to reduce the interceptability of a radar relative to its performance is to give the radar a processing gain not available to the ESM receiver. (***EW 102 David L. Adamy)***

We can think that radars have three levels of LPI.

1. The radar is easily detectable but not easily identifiable, also called LPID radar
2. The radar can detect a target and is not detectable by an ESM or RWR receiver at the same range but outside its illumination range.
3. The radar can detect a target and is not detectable by the ESM or RWR receiver on board the target; this is identified as "Quite Radar."

Characteristics of the LPI radar

The characteristics that distinguish an LPI radar from a conventional radar are the following:

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- Low sidelobe antennas,
- Irregular antenna scan patterns
- High duty cycle / wide band transmission,
- Accurate power management
- Carrier frequency
- Very high sensitivity
- High process gain
- Coherent detection
- Monostatic / Bistatic configuration.

LPI Radar waveforms

Several LPI radar techniques available to the modern radar designer can be used individually or in various combinations, depending on the application. By reducing the radar's effective radiated peak power (ERP) using some form of pulse, the compression technique is the most common LPI radar technique. The goal is to spread the radar signal over a wide bandwidth and over a period of time. This is typically done with frequency modulation, phase shift and frequency shift techniques (***McRitchie and McDonald 1999)***

1. Radar a onda continua a modulazione di frequenza (FMCW).
2. Phase Shift Keying (PSK)
3. Binary Phase Shift Keying (BPSK)
4. Barker Code
5. Compound Barker Code
6. Pseudo Random Code
7. Polyphase Code
8. Frank Code (P1- P2 – P3 – P4 Code)
9. Polytime Code (T1 -T2 -T3 – T4 Code)
10. Frequency Shift Keying (FSK)
11. Hybrid FSK/PSK

DETECTION OF LPI RADARS

“LPI modulations cannot be properly processed with ‘snap shots’ of data. These signals will require the collection of continuous streams of data. We can collect and process all current threat signals with current receivers but will need digital receivers to detect LPI signals.”

Electronic Warfare Support (ES) receivers must perform the tasks of detection, parameter identification, and classification in a complex environment of high noise interference and multiple signals in order to exploit LPI radar signals. Detection of LPI radar signals requires a large processing gain because of the wideband nature of the LPI radar. The basic idea behind the use of wideband signals is to spread the radiated power over a large bandwidth in order to produce a Power Spectral Density (PSD) below the noise at the receiver input. Under these conditions, detection is only possible if the signal is integrated over a long observation time. During that time, a special

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integration procedure must be used to ensure that the noise is not being added in the same amount (Burgos-Garcia et al. 2000, 23-28).

Another problem faced by the ES receiver is to provide sufficient sensitivity for detecting LPI radar signals with wide spectrum properties while discriminating against the multitude of high peak power, short duration conventional radar signals in the same band.

LPI radars are assumed to be low power, high duty cycle signals with phase or frequency coding. As the coding is unknown and can be complex, and assuming the frequency is also unknown, then coherent detection is not possible and non-coherent detection must be performed first. To achieve the maximum sensitivity the RF and video bandwidth must be matched to the signal modulation allowing detection of the total signal energy ***(Rayit and Mardia 1994, 359; 359-362; 362).***

The detection process is followed by the task of classification. Classification requires sorting the signal into groups having similar parameters. Parameters such as:

- LPI radar type
- Carrier frequency
- Modulation bandwidth
- Modulation period
- Code period
- Time and angle of arrival.

These are the parameters that distinguish one LPI radar signal from another and they are required for effective exploitation (jamming). Correlation with existing signals in a database (identification) can then aid in signal tracking and response management. To identify the emitter parameters, Fourier analysis techniques have been used as the basic tool. From this basic tool, more complex signal processing techniques have evolved, such as the short-time Fourier transform (STFT), so as to track signal parameters over time. More sophisticated techniques have also been developed, called time-frequency and bi-frequency distributions, to identify the different modulation schemes used by the LPI radar. These techniques include the Wigner Ville Distribution (WVD), Quadrature Mirror Filter Bank (QMFB), and Cyclostationary Processing (CP) (Pace 2004, 455).

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EXAMPLES OF LPI RADAR

On the battlefield, situational awareness and threat evaluation are achieved using tactical surveillance radars to detect and track targets. For covert operations, detection and tracking of targets should be as quiet as possible. These systems should employ LPI technology to decrease the probability of passive detection by hostile forces; that is, “to see without being seen.” The role of multimode airborne fire control radar is to provide the eyes for tactical fighter aircraft within an air dominance mission and also should employ LPI radars ***(Pace 2004, 455).*** In this section some examples of air, maritime, and land based LPI radars will be given from the open literature.

1. Airborne LPI Radars

Airborne LPI radars are used for target searching, tracking, location, identification, acquisition, designation, target imaging, periscope detection and weapon delivery. These LPI radars also have modes for covert navigation, weather detection, terrain following and terrain avoidance.

2. Maritime LPI Radars

Just as LPI techniques are useful for covert navigation and targeting for air applications, they are equally useful for covert maritime applications. LPI is well suited for this environment as the relatively slow speed of the ship allows for long integration times and extremely large radar cross-sections (RCSs).

In the maritime environment, the most significant threat to navies is anti-ship cruise missiles (ASCMs) with LPI seekers. These ASCM seekers will have power-managed operation in the 8-20GHz range as well as 35-96GHz ranges, by incorporating a number of advanced electronic technologies. These technologies will enable the missile to generate a broad collection wideband programmable waveforms with bandwidths reaching 500MHz to 1GHz. Using a variety of wideband techniques and coherent range-Doppler processing, these seekers will effectively target low RCS ships while simultaneously allowing the seeker to escape detection and reject decoys such as chaff

3. Land Based LPI Radars

There are many examples of land-based LPI radars generally performing ground surveillance and short-range air surveillance. In the case of ground surveillance role, these radars can be used to covertly detect ground targets because long integration times are possible. In the air surveillance role, the high speed of ingressing aircraft does not permit for extended integration times but typically these radars are used to cue short-range SAM systems. LPI can also be used effectively in the detection of hovering helicopters. Since there is a little motion, long integration times can be used and this helps the radar to detect the target even though it is embedded within the surrounding clutter ***(McRitchie and McDonald 1999,).*** The following are examples of land based LPI radars.

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ES RECEIVER CHALLENGES

To detect LPI radar signals, ES receivers have to overcome three main difficulties. These are:

- Processing gain of the LPI radar
- High sensitivity requirement
- LPI radar's coherent integration

Radar Processing Gain

Range Advance Factor (RAF) as α = $\frac{R_1}{R_r}$. where R_1 was the detection range of the ES and R_r was the detection range of the radar. If α > 1, the radar will be detected by the ES receiver, On the other hand, if α ≤ 1 the radar can detect the platform while the ES receiver platform cannot detect the radar.

LPI radars are effective against some ES receivers when a low-peak power and long duration signal is used with a large time-bandwidth product.

Large bandwidth signals greater than 10MHz which give 15 meters range resolution may not be needed unless a very high range resolution is required. This implies that signals of relatively narrow bandwidths and high duty cycles are effective for LPI applications.

An effective time-bandwidth product (processing gain) of around 1000 or 30dB with 10MHz modulation bandwidth and 1ms integration time is practicable and can be achieved with some LPI radars. ***(Lee 1991, 55)***

ES Receiver Sensitivity

Some ES receivers do not have sufficient sensitivity for the detection of LPI radar signals. Mr. Jim P. Lee states that a system sensitivity requirement of about -100dBmi will be adequate even for over-the-horizon operation.

The ES receiver has three basic means for increasing its sensitivity: increasing the antenna gain, reducing the pre-detection bandwidth and reducing the post-detection bandwidth. In order to improve sensitivity further, both the noise figure and transmission loss of the ES receiver should be minimized.

The first two means involve a probability of intercept (POI) loss by reducing either the angular or frequency instantaneous coverage.

The third merely represents a reduction in the measurement bandwidth of the intercept receiver. Therefore, for operation against high duty cycle LPI waveforms, there is scope within conventional ES receivers for increasing sensitivity at negligible cost by reducing the post-detection bandwidth without compromising the POI ***(Ruffe and Stott 1992, 200; 200-202; 202).***

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The table below shows the results from calculations of free space detection ranges for the PILOT radar, one of the most common FMCW tactical navigation LPI radar, compared with a conventional pulsed radar at 10kW peak power. The detection ranges are calculated assuming that frequencies and antenna beams all coincide in time.

Comparison of Radar Detection and ES Receiver Ranges

Radar Output Power	**Radar Detection Range (KM)**		**ES Receiver Intercept Range (km) (RCS = 100m²)**		
	100m² Target	**1m² Target**	**δ_I -40dBmi**	**δ_I -60dBmi**	**δ_I -80dBmi**
PILOT MK3					
1W	**28**	**8.8**	**0,25**	**2.5**	**25**
0.1W	**16**	**5**	**0**	**0.8**	**8**
10 mw	**9**	**2.8**	**0**	**0.25**	**2.5**
1mW	**5**	**1.5**	**0**	**0**	**0.8**
Conventional Pulsed Radar 10kW Radar	**25**	**7.9**	**25**	**250**	**2500**

It can be seen from Table that the PILOT radar with 1W output power can detect its 100m² RCS target at 28km, whereas its transmissions can only be intercepted at 0.25km with -40dBmi sensitivity. It can also be seen that the ES receiver interception range is coming closer to the radar's maximum detection range with -80dBmi sensitivity. ES receiver interception range can be calculated as 250km, too much above radar's
maximum detection range if the sensitivity of ES receiver were -100dBmi.
The table also shows that the effectiveness of LPI radar performance is strongly influenced by the radar cross-section of the target to be detected. If the PILOT radar were required to detect a smaller target, for example, an aircraft with an RCS of 1m², transmitted power of 1W would give 8.8km radar detection range, and the ES receiver with -80dBmi sensitivity would intercept PILOT radar much before it detects aircraft.

ES RECEIVERS FOR LPI RADAR DETECTION

Some wide-open ES receivers such as the Instantaneous Frequency Measurement (IFM) and Crystal Video Receivers (CVR) work well in a low-density signal environment where the pulses are short in duration. However, they are susceptible to interference in dense signal environments where radar pulses overlap in time. This problem has become more severe with the introduction of pulse compression waveforms and pulse-Doppler radars with their higher duty cycles. The problem associated with signal overlap may become worse with LPI signals which are expected to maintain even higher duty cycles.

On the other hand, LPI signals are expected to be much lower in peak power, and thus those LPI radars which are far away will not affect the performance of the ES receiver. However, there are likely to be "friendly" LPI radars on the same platform or nearby which will cause interference.

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As a result, with the proliferation of pulse compression and LPI signals, current wide-open IFM and crystal video receivers will be more susceptible to interference and thus are poor candidates for future ES receiver systems. In addition, they do not have the sensitivity for the detection of current and projected LPI signals (Lee 1991, 55).

With a scenario involving an FMCW LPI radar and an IFM receiver, the effects of processing gain and sensitivity on detection ranges can be seen. In the scenario 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 (MOP). Parameters of both FMCW LPI radar and IFM receiver are based on a reported calculation described in ***(Stove, Hume, and Baker 2004, 249-260).*** These parameters are given in the Table below.

Parameters of the FMCW Radar and IFM Receiver System

RADAR TYPE	**FMCW**	**ES RECEIVER TYPE**	**IFM**
Mean Transmitter Power	**1W**	**IF Bandwidth**	**2GHz**
Antenna Gain	**30dB**	**ES Receiver Antenna Gain**	**0dB**
Antenna Sidelobe Level	**-35dB**	**Video Bandwidth**	**10MHz**
Effective Radiated Power (ERP)	**60dBmi**	**Effective Bandwidth**	**200MHz**
Frequency	**9GHz**	**Processing Losses**	**3dB**
Integration Time	**1ms**	**Minimum SNR for Detection**	**17dB**
Bandwidth	**1KHz**	**Net Sensitivity**	**-60dBmi**
Received Power at 20km Range	**-125dBm**	**Incident Power Density from 60dBmi at 2.5km**	**-19 dBm/m²**
Target RCS	**100m²**	**Received Power at 2.5km**	**-60dBm**
Noise Figure	**4dB**	**Noise Figure**	**10dB**
Noise Floor	**-144dBm**	**Noise Floor**	**-80dBmi**
Incoherent Integration Gain	**4dB**	**Effective Aperture**	**-41dBm²**
SNR at 20km Range	**15dB**		
Agile Bandwidth	**100MHz**		

It can be calculated from the parameters in Table that the FMCW radar can detect its target at 20km range, while its transmissions can only be intercepted at 2.5km by the IFM receiver. If the FMCW radar 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 IFM receiver will easily detect the radar emissions before the radar system detects its target. As a result,

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it can be seen that although an IFM receiver can be suitable for low duty cycle pulsed radars, it is not a suitable ES receiver for LPI radar detection.

Following are some potential ES receiver architectures to be discussed for the detection of LPI radars. These potential architectures are by no means the only candidates for LPI detection, even though they are the best known today. There are other types of receivers not discussed, such as the correlator and the fast scan superhet, which could be used for LPI signal detection ***(Stove, Hume, and Baker 2004, 249-260).*** Among these ES receivers acousto-optic and digital receivers are seen to be the strongest candidates for the LPI radar detection.

Channelized Receivers

This is a system of many narrowly spaced receiving channels used to measure RF. This aims to give the best of both worlds, having a large probability of intercept with a high degree of sensitivity. Each channel is a complete radio receiver tuned to a particular filter characteristic and the assembly of many channels constitutes a fully parallel receiver with inherently high data rate capabilities ***(Fuller 1990, 1-10).***

Channelized receiver techniques offer greater sensitivity than the IFM receiver described in the scenario, by dividing the IF bandwidth (of 2 GHz in the scenario) 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 with a lower noise figure an losses than the IFM based system. The detection range against the FMCW radar in th scenario with 1W will then be increased to 25km, i.e. it will be approximately equal to the FMCW radar's detection range.

A potential counter to this is the random noise (RN) radar. This can have a very instantaneous bandwidth and thus the intercept range will be reduced if the transmission bandwidth is greater than the channel bandwidth. This is due to 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 RN radar's 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 (**Stove, Hume, and Baker 2004, 249-260).**

Superhet Receivers

A lower-cost alternative to the channelized 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 analyze 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.

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Sensitivity of the Superhetrodyne Receiver

IFM Receiver Sensitivity	**-60dBmi**
Lower losses	**-3dB**
Lower Noise Figure	**-4 dB**
Narrower Bandwidth	**-22dB**
Nat Sensitivity	**-89dBmi**

Table shows the sensitivity of the superheterodyne receiver with the IFM receiver system sensitivity. Even in the ‘non-tuned’ case the receiver outlined in Table would still detect the main beam of the FMCW radar, in free space, at 70km range, i.e. considerably greater range than that at which the radar can detect its target ***(Stove, Hume, and Baker 2004, 249-260).***

Matched Incoherent Receiver (MIR)

The matched incoherent receiver overcomes the mismatch currently found between the bandwidths of radars and intercepts receivers ***(Stove, Hume, and Baker 2004, 249-260).***

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. The MIR would be matched to the RF information and information bandwidths of the radar, but not to its actual transmitted waveforms. This is because it still does not match to the phase of the signal as does a 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 the scenario above, the MIR would have an effective bandwidth of 200KHz, making it 30dB more sensitive than an IFM receiver. If MIR has 7dB improvement over the IFM receiver due to lower losses and noise figure which was assumed for the channelized receiver and the superhet receiver, the MIR will have a sensitivity of -97dBmi, giving it a free-space detection range of 177km against FMCW radar in the scenario ***(Stove, Hume, and Baker 2004, 249-260).***

Digital Receivers

Most recent receivers deployed for LPI radar detection are digital, using mainly Fast Fourier Transform (FFT) as a signal processing technique. With these digital processing techniques such as FFT, the processing gain of the LPI radar is overcome.

The most important advantage of implementing the digital receiver is the possibility of performing different digital signal processing algorithms, as the intercepted signals are stored in memory. There are some disadvantages for this receiver, such as restricted memory and the dynamic range due to low resolution of the analogue to digital converter (ADC).

Digital receivers, often called software radios, place a high-performance burden on the ADC, but allow a good deal of flexibility in post detection signal processing. ES receiver parameters of interest include sensitivity, dynamic range, resolution, simultaneous signal capability, complexity, and cost. Figure 45 shows a block diagram of wideband digital ES receiver ***(Pace 2004, 455).***

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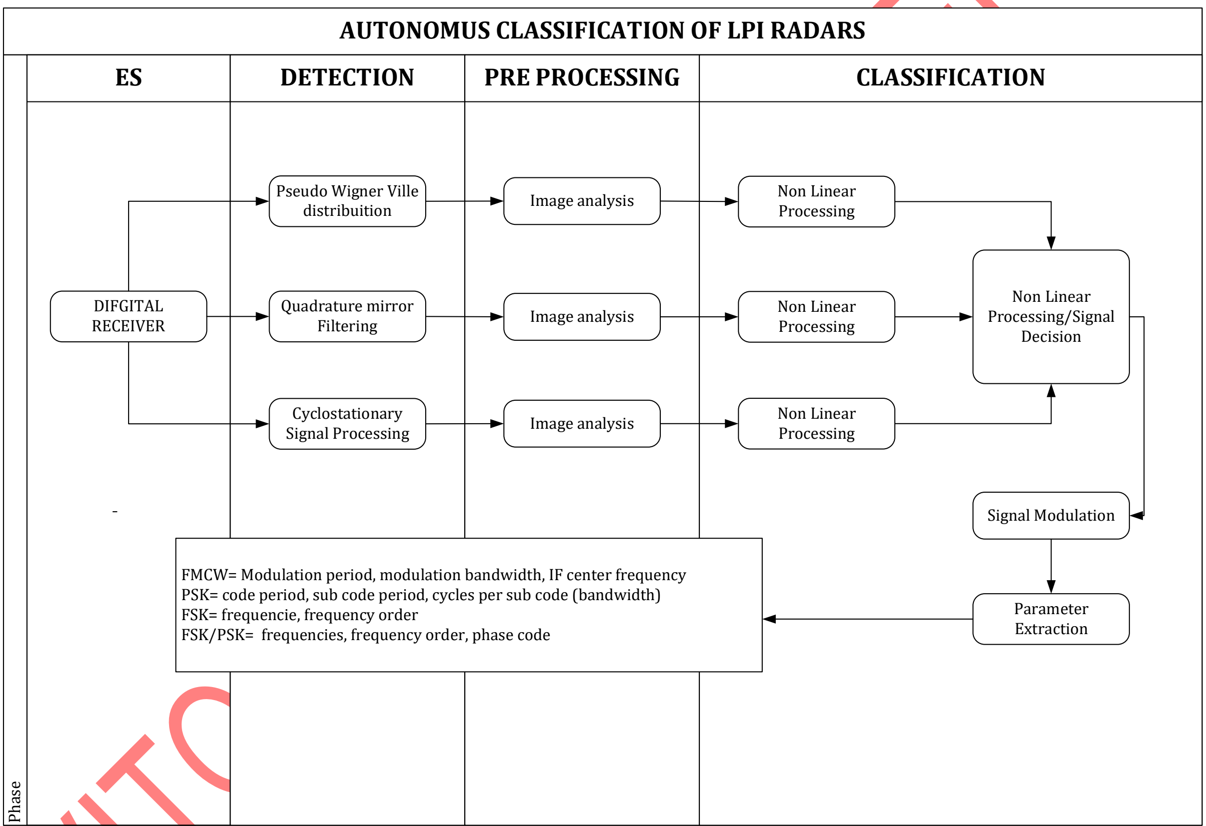
CLASSIFICATION OF LPI RADARS

A trained operator can use one or a combination of signal processing tools to detect the LPI waveform characteristics. For real-time tactical situations, such as EA being conducted against an LPI radar, the use of computers will provide the ultimate solution. A remaining problem is autonomous parameter extraction and classification. Trained operator eyes have no problem with this, once the signal processing results are obtained, but the question is how can this be done by a computer autonomously. This task is normally called specific emitter identification (SEI). SEI is a method of recognizing individual electronic emitters through the precise measurement of selected signal and characteristics. The problem that arises is that in order to be identified by SEI techniques, the emitter must have parameters that are stable and unique, within the measurement capabilities of the ES receiver. For LPI signals, this is typically not the case, since the signal is on for only a few code periods ***(Pace 2004, 455).***



The Figure above shows an example of a possible ES receiver used to detect and identify LPI radar signals. After being received and digitized, the type of modulation is determined first. The classification is done by using WVD, QMFB, CS, and possibly others, in parallel. Each algorithm provides its own neural network (NN) with the time frequency or bi-frequency image.

First a good amount of preprocessing must be done before the NN processed the image. The NN is trained with different LPI radar signals to recognize the numerous modulations that might be used by the LPI radar. Once the modulation type is identified, it is used to select the proper parameter measurement algorithm to process the timefrequency or bi-frequency output image. After the parameters of the signal are measured, the results are weighted to select the highest probable signal parameters, and then sorte into emitter classes by a clustering routine. It is only by directly digitizing the signal at the antenna, and taking advantage of high-speed parallel processing to run the sophisticated algorithms, that autonomous classification of LPI emitters can take place ***(Pace 2004, 455).***

CONCLUSION

The signal environment is changing at a rapid pace with new Low Probability of Intercept (LPI) radars coming into service worldwide. These radars exhibit lower power and higher duty cycle than previous radar technology. By 2010, approximately 30% of all radars will emit LPI signals and will be employed in all classes of radar including battlefield, navigation, surveillance, target acquisition and missile seekers on airborne, maritime, and land-based platforms ***(Tenix Defense 2005, 2).***

Airborne LPI radars are used for search, tracking, location, identification, acquisition, designation, target imaging, periscope detection, and weapon delivery. These LPI radars also have modes for covert navigation, weather detection, terrain following, and terrain avoidance. Just as LPI techniques are useful for covert navigation and targeting in airborne applications, they are equally useful for maritime applications. LPI is well suited for this environment as the relatively slow speed of a ship and extremely large radar cross sections (RCSs) allows for long integration times. Besides maritime applications, there are many examples of land-based LPI radar generally performing ground surveillance and short range air surveillance. In the case of the ground surveillance role, these radars can be used to covertly detect ground targets due to long integration times.

Electronic Warfare Support (ES) receivers currently in service are not optimized for the detection of LPI radars as they lack the sensitivity to detect the signals at sufficient range to provide military crews with an operational range advantage. LPI Radars use advanced radar and signal processing techniques “to see and not be seen” by ES receivers. To survive Electronic Attack (EA) and Anti Radiation Missile (ARM)
threats and mask their presence, LPI radars use:

- Low sidelobe antennas,
- Irregular antenna scan patterns,
- High duty cycle/wide band transmission,
- Accurate power management
- Carrier frequencies at peak atmospheric absorption,
- Very high sensitivity,
- High processing gain,
- Coherent detection,
- And monostatic/bistatic configurations.

There are several LPI radar techniques available to the modern radar designer that can be used singly or in various combinations, depending on the application. Reducing the radar’s peak effective radiated power (ERP) by using some form of pulse compression technique is the most common LPI radar technique. The objective is to spread the radar’s signal over a wide bandwidth and a period of time. This is typically done with frequency modulation (FM), which is the most common technique, phase shift keying (PSK), and frequency shift keying (FSK) techniques.

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To detect LPI radar signals, ES receivers have to overcome three main difficulties. These are:

· LPI radar's coherent integration,

· High sensitivity requirement,

· And processing gain of the LPI radar.

LPI radars have low power, high duty cycle signals with phase or frequency coding. As the coding is unknown and can be complex, and assuming the frequency isalso unknown, coherent detection is not possible and non-coherent detection must be performed first. To achieve the maximum sensitivity, the RF and video bandwidth must be matched to the signal modulation, allowing detection of the total signal energy ***(Rayit and Mardia 1994, 359; 359-362; 362).***

Detection of LPI radar signals also requires a significant processing gain because of the wideband nature of the LPI radar. Detection is possible if the signal is integrated over a long observation time.

Detection of LPI radar signals also requires sophisticated receivers that use time-frequency signal processing, correlation techniques and algorithms to overcome the processing gain of the LPI radar. Fourier analysis techniques have been used as the primary tool. More complex signal processing techniques have evolved from this essential tool, such as the short-time Fourier transform (STFT), to track signal parameters over time.

More sophisticated time-frequency and bi-frequency distribution techniques have also been developed to identify the different modulation schemes used by LPI radars. These techniques include the Wigner Ville Distribution (WVD), Quadrature Mirror Filter Bank (QMFB), and Cyclostationary Processing (CP) ***(Pace 2004, 455).***

These signal processing algorithms require large amounts of computing speed and memory. Managing processing speed is not a problem with current digital capabilities, but carrying enormous amounts of data is still difficult. Increasing the receiver's sensitivity allows for detecting sidelobes of the emitter while obligating the receiver to process a significantly large number of signals. Some wide-open ES receivers, such as the Instantaneous Frequency Measurement (IFM) and Crystal Video Receivers (CVR) work well in a low-density signal environment where the pulses are short. However, IFM and crystal video receivers are more susceptible to interference and thus are poor candidates for future ES receiver systems that perform LPI radar detection. In addition, they do not have the sensitivity required for detecting current and projected LPI signals ***(Lee 1991, 55).***

Calculations made by Dr Jim Lee show that to detect LPI radar, converter the receiver sensitivity must be on the order of -100dBm. The trend in ES receivers for LPI radar detection is toward digital receivers and incorporates the concept of digital antennas in which the analogue-to- (ADC) is at the antenna. The future digital receiver will incorporate optical technologies for speed and bandwidth and high-temperature superconductors for required sensitivities **(Pace 2006).**

Once the detection hurdle has been overcome, the ES receiver must next perform classification. Classification requires sorting the signal into groups having similar parameters.

These parameters are;

· LPI radar type,

· Carrier frequency,

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· Modulation bandwidth,
· Modulation or code period,
· Scan timing, i.e. where the radar is pointing at any time,
· And synchronisation, i.e., when the modulation pattern starts.

These parameters distinguish one LPI radar signal from another and are required for effective jamming. Correlation with existing signals in a database is called identification, signal tracking and response management. A trained operator can use a combination of signal processing tools to detect and classify the LPI waveform characteristics. For real-time tactical situations, such as EA being conducted against an LPI radar, speed and the decision-making of manual processing will not be fast, accurate, and sufficiently correct. In this case, autonomous parameter extraction, classification, and response management are required.

This necessitates the use of computers. After being received and digitised, the type of modulation is first determined. The classification is accomplished using WVD, QMFB, CS, and possibly other signal processing algorithms in parallel. Each algorithm provides its neural network (NN) with the time-frequency or bi-frequency image. The NN is trained with different LPI radar signals to recognise the use of numerous modules. The the the the the the the the the the the ctionsdigital that the LPI radar might havetion type is identified; it is then used to select the proper parameter measurement algorithm to process the time-frequency or bi-frequency output image ***(Pace 2004, 455).***

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