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Noisy Radar Interception Based on Using Detection Theory

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ABSTRACT

Low Probability of Interception (LPI) radars are difficult to be detected by interception devices and anti-radiation missiles due to their special properties. Using techniques such as transmission power reduction, these radars significantly reduce the probability of interception for intercept receivers. Noisy radar is a type of Low Probability of Interception (LPI) radars that reduces the probability of interception using a noise-like waveform. This paper intends to study this particular type of radar, and intercept it in intercept receivers. Furthermore, using detection theory, and also known or unknown parameters of the noisy radar's transmitted wave, the probability of interception is studied in these radars.

Keywords: Low Probability of Interception, Noisy radar, Detection Theory, MATHEMATICA, Random Noise Radar, SNR, MIMO

I. INTRODUCTION

Radar systems determine the existence of targets (and their specifications such as their distance or speed) in their operation environment through sending a signal to the surrounding space and analyzing the possible reflected signals. A radar is exposed to interception systems, electronic warfare and also anti-radiation missiles due to its signal-transmission property and therefore may become vulnerable to them. This has resulted in the formation of a series of discussions concerning low probability of interception (LPI) radars in the literature. By modifying the transmitted signal's properties, these radars provide the proper condition for reducing radar interception probability by interception devices. There are various methods for converting a radar to an LPI radar, including a reduction in the transmission power level, an increase in the transmitted signal's bandwidth, the use of irregular and unknown waveforms (such techniques can be seen in noisy radars and pulse coding radars), and several other techniques. Noisy radar is a type of low probability of interception (LPI) radars. A Random Noise Radar (RNR) system sends random-amplitude or pseudo-random-amplitude waveforms and then obtains the target's velocity and distance. Block diagram of an RNR system is shown in Fig. 1.

By studying, investigating and collecting data from various sources and making conclusions, a proposed method is studied and analyzed in this article using MATHEMATICA simulator software. LPI radars has been widely developed in recent works for example in [1] radar radiation of LPI radars have been analysed and then proposed a model to control the power allocation for LPI radars. Also machine learning develop recognition in LPI radars like [2] and [3]. Several works have been published on noisy radars such as [4] that particularly consists of two main parts. In the first part, low probability of interception (LPI) radars are introduced and their properties are investigated. These radars are important and critical at war. Another important issue in low probability of interception (LPI) radars is their interception. In the second section, the issues related to these radars are presented, including the subject matter of interception. An algorithm for noisy radars' interception is presented in [5]. In this reference, first, a noisy radar's signal analysis in the frequency domain is done and then, using the hypothesis test, noisy radars are detected. Finally, noisy radars' interception probability in various modes are calculated. A method for the detection of a noisy radar's signal is shown in [6]. The detection is done through a correlation test. First, human activities are detected using a correlation test and then these activities are detected with the assumption that the radar's signal passes through the wall and loses a significant amount of energy. In [6] noisy radars are used to detect human activities. Complex calculations for the interception of noisy radars are shown in [4] that can be used for the aim of this study. These calculations are mathematical models for received signals and are used for detection. This article deals with the analysis of the received signals in noisy radars, their installation method and finally their data processing approach. In [7] three modes in which the conditions are non-ideal are investigated in noisy radars, which are:

- Auto-correlation function in the transmitted signal is non-ideal
- The transmitted random signal is non-Gaussian
- Converting a continuous problem to a discrete one

A noisy radar's performance is investigated in the presence of the above modes. The fact that the noisy radar's performance in these conditions is similar to its performance in an ideal model is shown in this reference. In [8] first, the general issues concerning a noisy radar are investigated. Then, the correlation formula for detection is studied in these radars, and finally, a numerical example is simulated. In the next section, the average energy, correlation, and auto-correlation of a random signal modulated on frequency are shown. Then, a closed form for various SNRs introduced in the article is presented. MIMO systems in noise radars are presented in [9]. One of the most important issues regarding these systems is the interference between MIMO systems antennas. In this reference, the signals are made in such a way that their correlation with other antennas' signals is avoided. The signals that lack correlation are called orthogonal signals. In this reference, a rotational algorithm is presented that works in the transmitter part, and greatly reduces the interference by making noisy band-limited signals that have low correlation with each other. [10] examines the important advantages and challenges of noisy radar systems. Furthermore, it presents the results for radar functions, based on which their various capabilities can be shown.

The received signal in a radar interception device includes a noisy radar whose parameters, such as noisy signal variance, are whether known or unknown to us.

II. SYSTEM MODEL

Noisy radar ability is important in Doppler distance and frequency simultaneous measurement. Fig.1 shows the overall schematic of a noisy radar system.
is a signal sent to surroundings by radar, suppose that this signal crashed to an animated target with velocity v and distance d from radar, and its reflection has reached us.
We have to know $S(t)$ nature first:

$$S(t) = [X(t) + jY(t)]\exp(2\pi f_c t)$$

Where f_c is carrier frequency. $X(t)$ and $Y(t)$ are Gaussian process with average zero. As indicated in Fig.1, $S(t)$ is the transmitted signal.

The purpose is to decide on using this received signal, regarding the presence or absence of noise radar signal in the surroundings. In other words, we have an interception device to show the receiver's noise process with series $W[n]$.

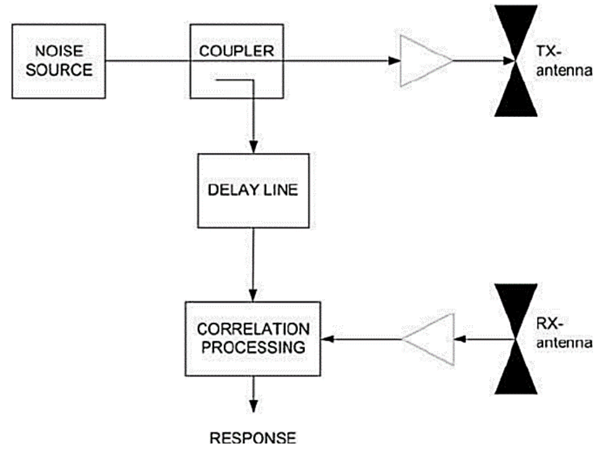

Figure 1. General Schematic of noisy radar

The primary problem of this article is a detection problem with the following assumption test:

$$\begin{cases} H_o : r[n] = W[n] & n = 0,1,\ldots, N-1 \\ H_1 : r[n] = S[n] + W[n] & n = 0,1,\ldots, N-1 \end{cases}$$

In this relation, $r[n]$ is the signal measured by the interception device. $S[n]$ and $W[n]$ are the noisy radar's possible signal sample and the noisy signal sample of the interception device's receiver, respectively. $S[n]$ is a Gaussian process with a zero mean and σ_s^2 as variance. $W[n]$ is a Gaussian process with a zero mean of and σ^2 as variance. Our goal is to design a detection using measured signal $r[n]$ so as to decide on whether it properly belongs to the H_0 or H_1 hypotheses.

III. DETECTION

For each radar two possibilities are defined based on which the radar's performance is studied. The probability for the correct detection of a target has a value of p_d, and on the other hand, the probability for the false detection of a target has a value of p_{fa}. Suppose that a target is at distance d from the radar. Then detection probability and false alarm probability are defined as:

$$\begin{aligned} P_d &= P\{\text{Decide}H_1 \mid H_1\text{occurrence}\} \\ &= P\{\text{deciding target existence} \mid \text{target exists}\} \\ &= P\{\text{deciding target existence} \mid \text{target does not exist}\} \end{aligned}$$

Neyman–Pearson Theory

Assume that ($X_1, X_2, \ldots, X_n$) are random samples with distribution function $f(x \mid \theta)$. to show Neyman–Pearson theorem, assume that we have two decision-making statistics as follow:

$$\begin{aligned} \mathrm{H}_0 &: \mathrm{N}\ (0,1) \\ \mathrm{H}_1 &: \mathrm{N}\ (1,1) \end{aligned}$$

This problem is binary. In receivers, if $x[n] < 1/2$ is received, H_1 is chosen and if $x[n] > 1/2$ is received, H_0 is chosen.

Now, the probability of H_1 being sent and detected correctly is called the detection probability, which is:

$$\begin{aligned} P_d &= P(\mathrm{H}_1; \mathrm{H}_1) \\ &= Pr\{x[0] > \gamma; \mathrm{H}_1\} \\ &= \int_\gamma^\infty \frac{1}{\sqrt{2\pi}} \exp[-\frac{1}{2}(t-1)^2]dt \\ &= Q(\gamma - 1) \end{aligned}$$

In the above equation, $Q(.)$ is $Q-Function$. Moreover, false alarm probability is:

$$\begin{aligned} P_{FA} &= P(\mathrm{H}_1; \mathrm{H}_0) \\ &= Pr\{x[0] > \gamma; \mathrm{H}_0\} \\ &= \int_\gamma^\infty \frac{1}{\sqrt{2\pi}} \exp[-\frac{1}{2}t^2]dt \\ &= Q(\gamma) \end{aligned}$$

In the aforementioned example, we have $\gamma = 1/2$.

Assuming that variances σ_s^2 and σ^2 are known or unknown, the above hypothesis test can be solved using the Neyman-Pearson criterion. Neyman-Pearson theory is defined as:

$$L(x) = \frac{p(x; \mathrm{H}_1)}{p(x; \mathrm{H}_0)} > \gamma$$

IV. THE PROPOSED METHOD

In this section, detection statistic for the detection of noisy radars is presented. If a noisy radar is in the surroundings, the received signal of the interception device receiver is H_1 and otherwise it is H_0.

$$\begin{cases} \mathrm{H}_0 & \Rightarrow x[n] = w[n] \\ \mathrm{H}_1 & \Rightarrow x[n] = s[n] + w[n] \end{cases}$$

In the above equation, $s[n]$ is Gaussian random signal $\mathrm{N}\ (0, \sigma_s^2)$ and $w[n]$ are Gaussian random signals with $\mathrm{N}\ (0, \sigma^2)$ parameters

Known Signal and Noise Parameters

In this section, the simplest type of detection is studied. In this type of detection, both the noisy radar's signal parameters and the environment's noise parameters are known. In this section, the estimation of the parameters is not needed. Therefore, we have:

$$\begin{cases} \mathrm{H}_0 & \Rightarrow X \sim \mathrm{N}\ (0, \sigma^2 I) \\ \mathrm{H}_1 & \Rightarrow X \sim \mathrm{N}\ (0, (\sigma^2 + \sigma_s^2) I) \end{cases}$$

Assuming that both σ^2 and σ_s^2 are known parameters, Neyman-Pearson receiver regards hypothesis H_0 as correct, if:

$$L(x) = \frac{p(x; \mathrm{H}_1)}{p(x; \mathrm{H}_0)} > \gamma$$

The Gaussian random parameters distribution function is taken into account. Thus, we have:

$$L(x) = \frac{\dfrac{1}{[2\pi(\sigma_s^2 + \sigma^2)]^{\frac{N}{2}}} \exp\Big[-\dfrac{1}{2(\sigma_s^2 + \sigma^2)} \sum_{n=0}^{N-1} x^2[n]\Big]}{\dfrac{1}{(2\pi\sigma^2)^{\frac{N}{2}}} \exp\Big[-\dfrac{1}{2\sigma^2} \sum_{n=0}^{N-1} x^2[n]\Big]} > \gamma$$

In the above equation:

$$\gamma = Q^{-1}(P_{FA})$$

In order to obtain the detection statistic, we have:

$$ln(L(x)) = \frac{N}{2} ln(\frac{\sigma^2}{\sigma^2 + \sigma_s^2}) - \frac{1}{2}(\frac{1}{\sigma_s^2 + \sigma^2} - \frac{1}{\sigma^2}) \sum_{n=0}^{N-1} x^2[n]$$
$$= \frac{N}{2} ln(\frac{\sigma^2}{\sigma^2 + \sigma_s^2}) + \frac{1}{2} \frac{\sigma_s^2}{\sigma^2(\sigma_s^2 + \sigma^2)} \sum_{n=0}^{N-1} x^2[n]$$

The H_1 hypothesis is considered to be correct if:

$$\mathrm{H}_1 = \mathrm{TRUE\ IF}\ \ ln(L(x)) > ln(\gamma)$$
$$\Downarrow$$
$$\frac{N}{2} ln(\frac{\sigma^2}{\sigma^2 + \sigma_s^2}) + \frac{1}{2} \frac{\sigma_s^2}{\sigma^2(\sigma_s^2 + \sigma^2)} \sum_{n=0}^{N-1} x^2[n] > ln(\gamma)$$
$$\Downarrow$$
$$\frac{1}{2} \frac{\sigma_s^2}{\sigma^2(\sigma_s^2 + \sigma^2)} \sum_{n=0}^{N-1} x^2[n] > ln(\gamma) - \frac{N}{2} ln(\frac{\sigma^2}{\sigma^2 + \sigma_s^2})$$
$$\Downarrow$$
$$\frac{1}{N} \frac{\sigma_s^2}{\sigma^2(\sigma_s^2 + \sigma^2)} \sum_{n=0}^{N-1} x^2[n] > \frac{2}{N} ln(\gamma) - ln(\frac{\sigma^2}{\sigma^2 + \sigma_s^2})$$
$$\Downarrow$$
$$\frac{1}{N} \sum_{n=0}^{N-1} x^2[n] > \frac{\sigma^2(\sigma_s^2 + \sigma^2)}{\sigma_s^2} \Big[\frac{2}{N} ln(\gamma) - ln(\frac{\sigma^2 + \sigma_s^2}{\sigma^2})\Big]$$
$$\Downarrow$$
$$T(x) = \frac{1}{N} \sum_{n=0}^{N-1} x^2[n] > \gamma'$$

Unknown Signal Parameters

In this section, due to the unknown nature of the detection parameters, first, the parameters have to be estimated. In this case, the Neyman-Pearson receiver considers hypothesis H_0 to be correct, if:

$$L(x) = \frac{\max_{\hat{\sigma}^2} p(x \mid \hat{\sigma}^2, \mathrm{H}_1)}{p(x \mid \mathrm{H}_0)} > \gamma$$

Now, to organize the above equation, $\hat{\sigma}^2$ parameter has to be estimated. In order to estimate this parameter based on MLE method, the following steps are done:

$$\frac{\partial ln\, p(x\,|\,\hat{\sigma}^2, \mathrm{H}_1)}{\partial \sigma^2} = 0$$
$$\Downarrow$$
$$-\frac{N}{2\hat{\sigma}^2} + \frac{1}{2\hat{\sigma}^4}\sum_{n=0}^{N-1} x[n]^2 = 0$$
$$\Downarrow$$
$$\hat{\sigma}^2 = \frac{1}{N}\sum_{n=0}^{N-1} x[n]^2$$

So far, the formation of the detection statistic and the estimation of the parameters have been presented. Next, in order to present a proper method for detection, the Chi Square Distribution function has to be introduced.

V. CHI SQUARE DISTRIBUTION

If standard normal distribution Z has an exponent of 2, the Chi Square Distribution with one degree of freedom will be obtained (since we have chosen only one standard normal variable).

$$Z = \frac{(x-\mu)^2}{\sigma^2}$$

Where variable x has a normal distribution with a mean of μ and standard deviation σ^2. Chi Square Distribution values vary as the degree of freedom is changed. If we add up n independent standard normal observations, the resulting variable has Chi Square Distribution with n degrees of freedom.

$$z = \sum_{i=1}^{n} \frac{(x_i-\mu_i)^2}{\sigma^2}$$

The only parameter for Chi Square Distribution is the degree of freedom (r). Therefore, the shape of the distribution changes according to the degree of freedom.

VI. SIMULATION

In the previous section, Chi Square random variables were investigated. In this section, using the aforementioned equations, the performance of the interception device against the noisy radars is studied. Furthermore, using detection statistic $T(x)$, the detection of noisy radars is also addressed.

$$T(x) = \sum_{n=0}^{N-1} x[n]^2$$

Based on the presented explanations and the Gaussian nature of variables $x[n]$, it can be concluded that $T(x)$ is a Chi Square random variable with N degree of freedom, then:

$$x \sim Normal$$
$$\Downarrow$$
$$T \sim Chi-Square$$

Based on the above-mentioned issues, the detection statistic T, subject to hypotheses H_0 and H_1, is as follows:

$$\begin{cases} T \sim \sigma^2 \mathrm{X}_N^2 & \mathrm{H}_0 \\ T \sim (\sigma^2+\sigma_s^2)\mathrm{X}_N^2 & \mathrm{H}_1 \end{cases}$$

Based on the detection statistic, the aim is to find the threshold limit value δ:

$$T \,£\,^{\mathrm{H}_1}_{\mathrm{H}_0}\, \delta$$

To find δ, using false alarm probability, we have:

$$\begin{aligned} P_{FA} &= Pr(T > \delta\,|\,\mathrm{H}_0) \\ &= Pr(\sigma^2 \mathrm{X}_N^2 > \delta) \\ &= Pr(\mathrm{X}_N^2 > \frac{\delta}{\sigma^2}) \end{aligned}$$
$$\Downarrow$$
$$\delta = \sigma^2 F^{-1}_{\mathrm{X}_N^2}(1-P_{FA})$$

Where $F^{-1}_{\mathrm{X}_N^2}$ is Chi Square cumulative inverse function.

In order to obtain the correct detection probability, we have:

$$
\begin{aligned}
P_D &= Pr(T > \delta \mid \mathrm{H}_1) \\
&= Pr((\sigma^2 + \sigma_s^2)\mathrm{X}_N^2 > \delta) \\
&= Pr(\mathrm{X}_N^2 > \frac{\delta}{\sigma^2 + \sigma_s^2}) \\
&= 1 - F_{\mathrm{X}_N^2}(\frac{\delta}{\sigma_2^2 + \sigma^2}) \\
&= 1 - F_{\mathrm{X}_N^2}(\frac{\sigma^2}{\sigma_2^2 + \sigma^2} F_{\mathrm{X}_N^2}^{-1}(1 - P_{FA}))
\end{aligned}
$$

In the following, the simulations are presented.

Known Parameters

In this section, there is no need to estimate the parameters. For various probabilities of false alarm, first, the threshold limit is obtained using equation 23. Then, 1000 samples of the hypothetical signals are made and after the generation of statistic T, the number of correct detections by the radar is reported as the probability of detection. Fig.2, Fig.3 and Fig.4 show the probability of detection for various probabilities of false alarm based on signal to noise ratio for N=1,8,16 when the parameters are known.

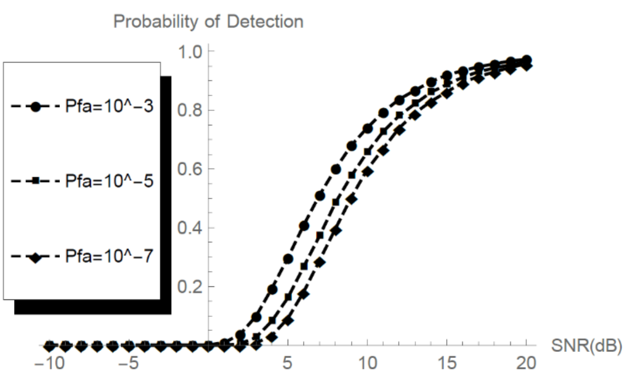

Figure 2 probability of detection for N=1 when parameters are known

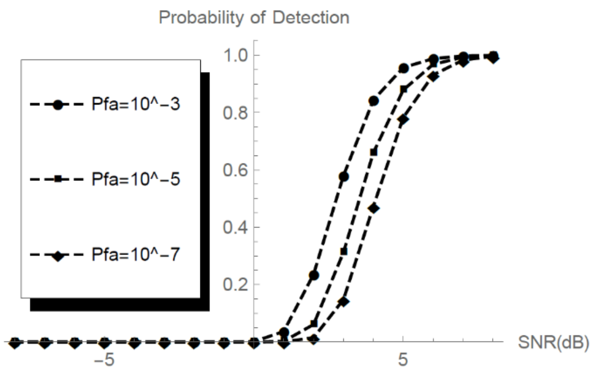

Figure 3 probability of detection for N=8 when parameters are known

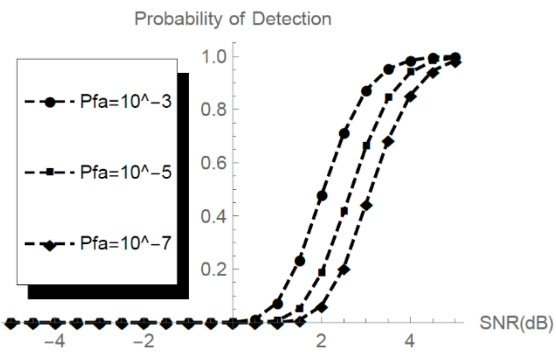

Figure 4 probability of detection for N=16 when parameters are known

Unknown Parameters

In this section, first, the signal's parameters are estimated, and then, as in the previous mode, detection of the noisy radar is addressed. For various probabilities of false alarm, first, the threshold limit is obtained using equation 23, and then, the signal's parameter is estimated. Next, 1000 samples of the hypothetical signals are made and after the generation of statistic T, the correct detections by the radar are reported as the probability of detection. Fig.5 and Fig.6 show the probability of detection for various probabilities of false alarm based on signal to noise ratio for N=1,8 when the parameters are unknown.

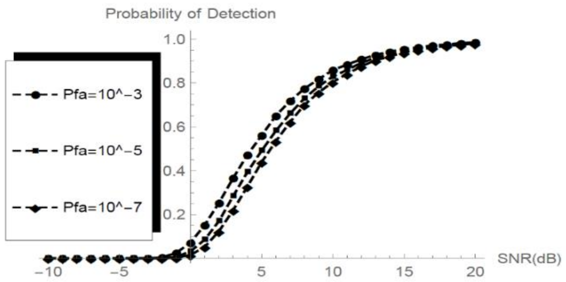

Figure 5 probability of detection for N=1 when parameters are unknown

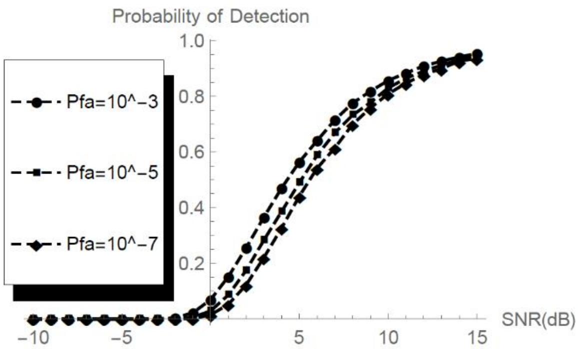

Figure 6 probability of detection for N=8 when parameters are unknown

VII. CONCLUSION

Due to the important role of radars in controlling and guiding strategic weapons, their discovery and detection can be crucial in the defense systems of planes, ships, and other important military equipment. In addition, obtaining precise information about the formation of radars in an area and the enemy's radar capabilities are of the utmost importance in major military decision-makings. Low probability of interception (LPI) radars hide themselves from the enemy’s military equipment. Low probability of interception (LPI) radars reduce interception by using techniques such as Gaussian noise transmission.

This article intends to intercept one of the most significant types of low probability of interception (LPI) radars. Noisy radars detect the targets in the surroundings by using Gaussian noise signals. These radars’ signals are Gaussian noise signals that are difficult to be detected by interception receivers. Using the GLRT method, this article presents an algorithm for the detection of the noise radar’s signal in an interception device receiver.

In the first section of this study, an introduction and a record of the researches done on the subject are presented for low probability of interception (LPI) radars. In the second section, the subject matter is investigated from the standpoint of the science of detection. In the 4th section, the problem is categorized into two modes. In the first mode the noise radar’s signal parameters are known for the interception device receiver. In this mode, due to the known nature of the noisy radar’s signal parameters, the detection and discovery of the noisy radar is simpler. On the other hand, in the second mode these parameters are unknown, and therefore the signal’s parameters have to be estimated at first, and then the radar’s discovery occurs. In the 6th section, simulation results of the two modes are presented. Based on the presented results in low SNR, the probability of detection is low, and an increase in this value leads to an increase in the probability of detection.

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