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## Algorithm for the Estimation of Time and Frequency Parameters of a Simple Pulsed Radar Signal

By

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### ABSTRACT

*In the field of Electronic Warfare (EW), the military make use of new forms of radar signal waveforms for security purpose in order to conceal some of its characteristics. As such, better signal processing tool is required to analyze the emitted signal for the detections of radar capabilities. An algorithm is developed in this paper based on time-frequency technique in order to estimate time and frequency parameter of the conventional simple pulsed radar signal. The Time-Frequency Distribution (TFD) used in this work is the spectrogram, the square magnitude of short-time Fourier Transform (STFT), with the aid of other statistical signal processing tools such as Hilbert transform, Instantaneous Frequency (IF) and Instantaneous Power (IP) in order to achieve the objective of this work. The appropriate functions in MATLAB R2014a that involved parameter estimation and of this aforementioned signal were used to implement the algorithms. The estimation and accuracy were validated using Monte Carlo simulation performed at various ranges of Signal-to-Noise Ratios (SNRs) in the presence of noise modeled by the Additive White Gaussian Noise (AWGN). Results obtained showed Probability of Correct Parameter Estimation (POCPE) of 100% at SNR equal or greater than XXdB for time-based parameters estimation and SNR equal or greater than XXdB for frequency-based parameter estimation is achieved.*

**Key words:** Additive White Gaussian Noise (AWGN) Electronic Warfare (EW), Signal-to-Noise Ratios (SNR), Probability of Correct Parameter Estimation (POCPE), short-time Fourier Transform (STFT).

### INTRODUCTION

Electronic Warfare (EW) is the art and science of preserving the use of the electromagnetic spectrum for friendly use while denying its use to the enemy through the usage of radar (Adamy, 2001). Radar is an electromagnetic sensor system for the detection and location of reflecting objects (Skolnik, 2008). It detects the position of an object in space to extract relevant information or to attack a given target via electronic means. Thus, EW applications cover the full radio frequency spectrum, such as the infrared

spectrum, the optical spectrum, and the ultraviolet spectrum (Adamy, 2006).

EW can be classified into three branches, namely:

- i. Electronic-Counter Counter Measures (ECCM)
- ii. Electronic Counter Measures (ECM)
- iii. Electronic Support Measures (ESM).

These branches of EW are further subdivided into different subcomponents as shown in Figure 1.0.

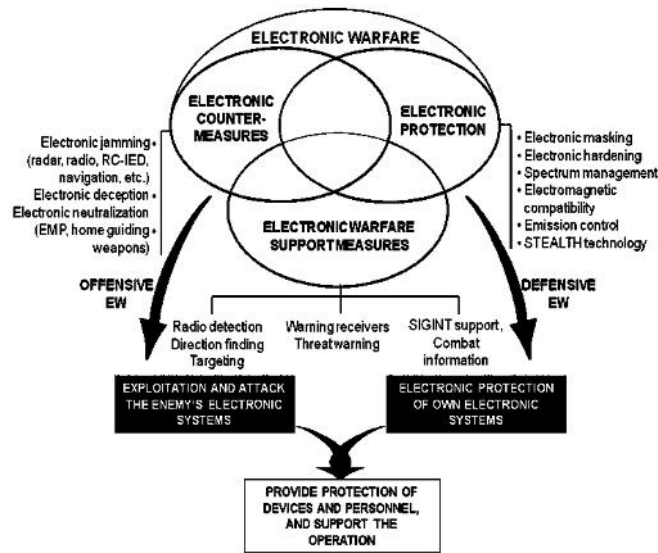


Figure 1.0: Classification of EW (Zsolt, 2014)

The ESM component of EW deals with tactical interception through the passive surveillance of the EM spectrum to detect the enemy's position, strength, and intention, besides warning of targets. ESM involves detection, recognition, tracking, targeting, warning, destruction, and avoidance. ECM also known as Electronic Attack (EA) involves the act of preventing or reducing the enemy's use of the EM spectrum (capabilities) and promotion of uncertainty. The ECCM component also known as Electronic Protection (EP) is the protection of friendly combat capability against undesirable effect of friendly or enemy employing the use of EM (Elsworth, 2010). The field of Electronic Intelligence (ELINT) for which this work finds practical application, is a major aspect of the ESM. ELINT is the process of analyzing radar signals in order to obtain information contained in these signals (Wiley, 2006). Radar application can be in airborne, land-based, or sea traffic (Neri, 2006). Radar uses radio waves to determine the range, altitude, direction or speed of objects. It is used to detect ships, aircrafts, guided missiles, space crafts, motor vehicles, weather formations, and terrains. The radar antenna or dish transmits pulses of radio waves or microwaves that bounce off any object in their paths. The object returns a tiny bit of the energy of the wave to an antenna or a dish that is usually located at the same site as the transmitter (Wolff,

2009). Besides the carrier frequency, an airborne radar signal can be characterized by the PRI and the Pulse Width (PW). Currently, radar signals can be roughly classified into three groups as follows (Elsworth, 2010) for which this paper would look into:

- i. Simple radar signal of simply modulated pulse and constant PRI (no agility)
- ii. Pulse modified radar signals such as the pulse compression and frequency hopping (frequency agility) radar signals used mostly by military to achieve Low Probability of Interception (LPI).
- iii. PRI modified radar signals used by different radar types to achieve specific functions (time agile/staggered PRI).

### Literature Review

Some major, recent, and relevant works related to the subject area of ELINT with respect to the proposed radar signal analysis are presented. Han *et al.*, (2013) employed an analytical-based novel method of radar signal analysis using game theory for frequency hopping radar waveforms. The work also investigated the design consideration of frequency hopping radar waveforms using MIMO radar. First, the research presented the MIMO radar signal model and the sparse representation. Then, the formulation

of a novel game model and a proposed two joint design algorithms were considered: one for applying a non-cooperative scheme and the other for applying a cooperative scheme. The game theory was used to compute the adaptive code matrix and amplitude matrix for these frequency-hopping waveforms. The study demonstrated the improvement of the resulting codes and amplitudes through numerical examples. However, other forms of radar signals with various time and frequency modulation were not considered and robust simulations were not used either Ahmad et al., (2014) surfaced a low-complexity method of Airborne Radar signal Type Analysis and Classification (ARTAC) system. This method explored the time-frequency analysis for achieving its objectives which involved the determination of Electromagnetic Order of Battle (EOB) in the field of electronic support system. A combination of instantaneous energy and spectrogram were used for analysis and the rule-based classifier was used for classification. Other signal processing tools such as the autocorrelation, based on the TFR and Frequency Modulation (FM) were used to assist tools employed in the analysis. Five various test signals were considered and the method achieved a classification accuracy of 90% at 6.2 dB. Thus, accurate frequency parameter estimations were not optimally achieved and as such the main focus of the work was shifted more towards the classification aspect. This shifted the method usage to serve more as an intercept radar signal parameters pre-estimation and characteristics pre-determination rather than correct parameters estimation first before classification. Mikucet al., (2016) investigated modified B-distribution and particle filters for the estimation and extraction of radar signals. Calculation of time-frequency representation was made using modified B-distribution, where the estimation procedure model represents one-time bin. An adaptive standard for the calculation of particle weighed coefficients whose main parameters were frequency integral squared error and estimated maximum of mean power spectral density per one-time bin was utilized. The analysis of the suggested estimation application was

executed on a generated signal in the absence of any noise and subsequently on modeled and recorded real radar signals. The benefit of the suggested method was in the solution of interrupted estimations of instantaneous frequencies which appeared when these estimations were determined according to maximum energy distribution, as in the case of intersecting frequency components in a multicomponent signal. Four cases were considered for the validation of the method chosen; modeled radar signal of pedestrian walking, radar signal of a moving vehicle, radar signal of a walking pedestrian, and composite radar signal with two targets. Results obtained showed lower error in instantaneous frequency estimation as compared to other methods. However, it was evidently clear that only the estimation of instantaneous frequency was considered. Further research should be carried out in order to estimate other time-frequency distribution parameters. Kishore et al., (2017) presented an improved signal processing technique developed for the analysis and classification of LPI radar waveforms. The intercepted LPI radar signals were classified based on the type of pulse compression waveform. They were classified as Linear Frequency Modulation (LFM), Nonlinear LFM (NLFM), Binary Frequency Shift Keying (BFSK), poly phase Barker, poly phase P1, P2, P3, P4, and Frank codes. The classification approach was based on the parameters measured from the preprocessed radar signal intercepted by Electronic Support (ES) or Electronic Intelligence (ELINT) system. Signal embedded within the noise was estimated using Wigner Ville Distribution (WVD) to improve the SNR. Features were then extracted using the time domain and frequency domain techniques. Further, parameters measured from the Fractional Fourier Transform (FRT) were used for the classification. Extensive simulations were carried out with different LPI radar modulated waveforms corrupted with Additive White Gaussian Noise (AWGN) of SNR up to -15 dB and impulse noise with 90 percentage of noise density. From simulation results, the technique classified all the various LPI modulations with 95% success rate at

lower SNRs as compared to the existing techniques such as Gaussian Chirplet time-frequency atoms. Despite achieving less computational complexity than the WVD methods typically used in LPI Radar modulation classification and the capability of classifying different types of LPI modulations with high success rate at a low SNR of -10dB, only some LPI signals were considered and focus was more on intra-pulse modulation.

Researches have been given significant attention in the field of ELINT for the development of algorithms for the analysis and classification of radar signals to determine its capabilities using time-frequency techniques. The research interests have also peaked in this area due to LPI signals of whose goal is “to see and not be seen” and as such ELINT researchers have to come up with new methods to address these types of radar signals. In the light of the literatures reviewed and argument presented, this work will focus on uniquely occupying the research gap of analyzing both the time and frequency changing (agility) aspects of incoming radar signals. This would involve testing signals of four types; no agility (simple pulsed), time agility (PRI modulated), frequency agility (frequency hopping) and time and frequency agility (agile pulsed). Secondly, the spectrogram TFD is chosen as the TFD due to its simplicity of its Fourier

transform origin and low computational complexity as compared to other TFDs.

## METHODOLOGY

### Generation of Radar signals

A single algorithm was created to generate the radar signals considered in this work. This gives a signal output of a radar signal at the end of algorithm to an input of six parameters required. Three of this parameter are time-based; the PW, PRI1 and the PRI2 while the remaining three are frequency based; carrier frequencies (F1, F2) and sampling frequency, Fs. The PW and Fs normally, remains the same irrespective of the signal in consideration in line with the scope of work; however, the PRI and carrier frequencies also remains the same due to the scope of this work focusing on the conventional simple pulsed radar signal of constant time and frequency parameters. The reason for this unique design of the algorithm is to allow for future expansions of this radar signal algorithm to other groups.

The first step taken in the algorithm designed for generation of signal is converting of time parameters from seconds (precisely microseconds for radar signals) to samples using the sampling frequency based on the common

$$t = NT_s = \frac{N}{F_s}; \therefore N = t * F_s \quad (1.0)$$

Formula as shown below;

Where t=time in sec; N= time in samples; Ts = sampling time and Fs = sampling frequency.

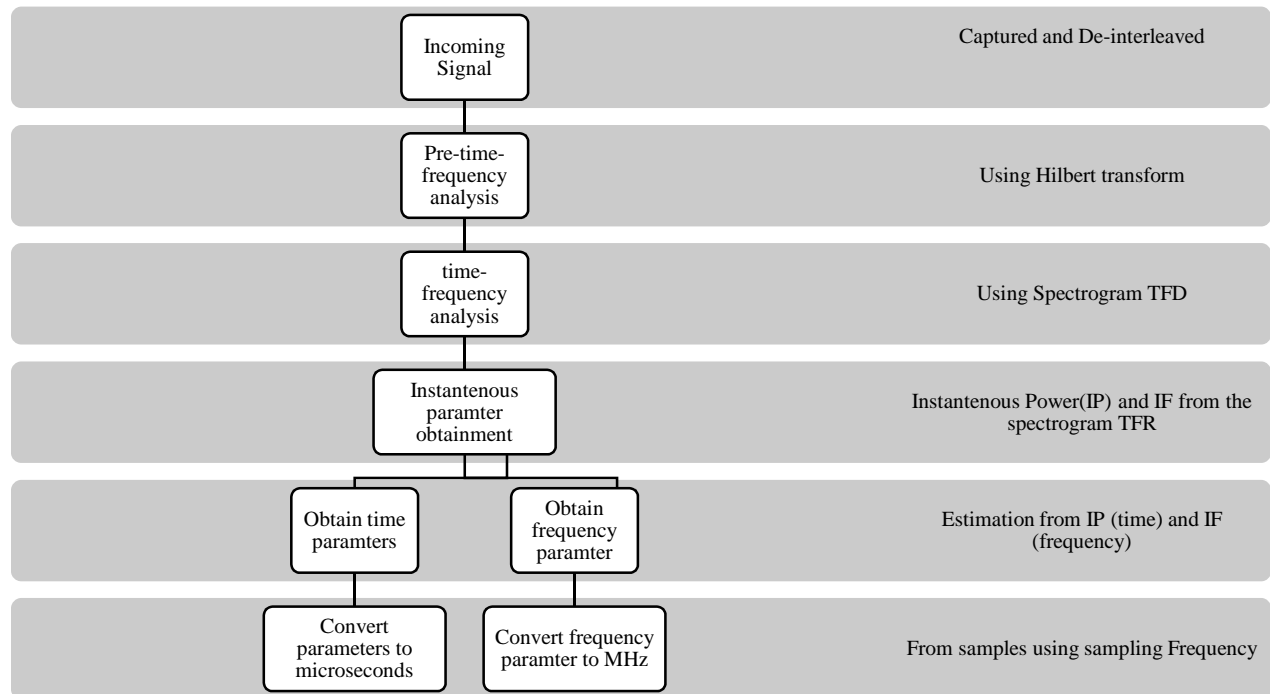
Thereafter, PW part of the signals is generated using a co-sinusoidal command at each carrier frequency for the duration of stipulated PW time and PRI part is gotten using ‘zeros’ command for the duration of the stipulated PRI times. The ‘zeros’ command in MATLAB is used to generate a matrix of zeros, it was also used to generate delay time (of 30 samples) at the beginning of each signal in order to simulate practical scenario of an incoming radar signals. Finally, the radar signal is now gotten by the cascading the aforementioned parts based on the

literatures presented. It should be noted that the cascaded option of generating this radar signal as opposed to other possible method (of the same result) such as filtering or use of loops was used in order to obtain a faster signal output.

### Signal Analysis

This depicts the major section of the work whereby an algorithm is generated to produce the accurate time and frequency parameters from the

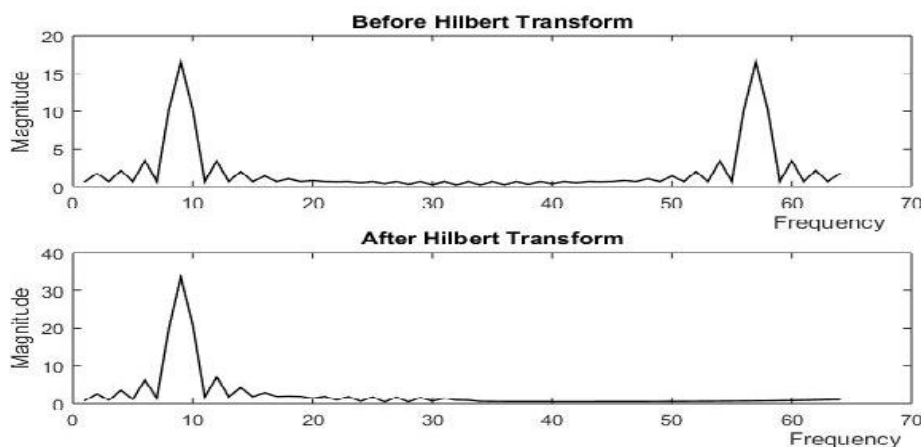
inputted incoming signal. A chart depicting process in presented in Figure 1.1



**Figure 1.1** Signal Analysis Process Depictions for Time and Frequency Characteristics Determination for a Radar Signal

Signal analysis algorithm from Fig. 1.1 can be roughly divided into five parts; Pre-time-frequency analysis (Hilbert analysis), time-frequency analysis

(spectrogram analysis), instantaneous parameters obtainment (IP and IF estimation), time and frequency parameters estimation and conversion.



**Figure 1.2** Illustration of the effect of Hilbert transform on radar signal

It can be seen in figure 1.2 that the upper part of the figure contains two frequencies due to the Fourier transform despite the fact the only a carrier frequency was used during the modulation of the

signal depicted and also the second one is an exact mirror of the first one. As such, the justification for using the Hilbert transform is shown in the lower aspect of the figure where the second mirror

frequency is eliminated and would still give required frequency information.

*Time-Frequency Analysis*

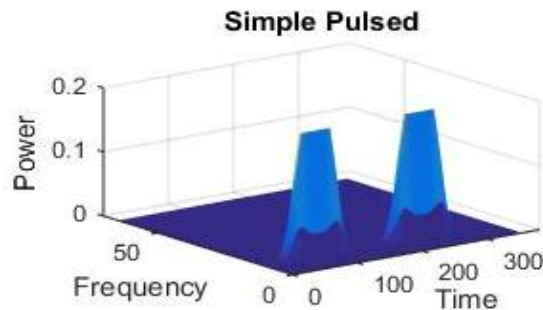
This aspect involves the use of the spectrogram TFD using STFT to analyze the time and frequency content of the signal in order to obtain its time-frequency representation (TFR). Basically, the code is constructed based on two inputs (the signal and window length) and gave a single spectrogram output containing power, frequency and time content of the input signal.

The spectrogram program consists of basically three parts;

- i. windowing in time;

- ii. Obtaining frequency equivalent using FFT
- iii. Obtaining the signal power.

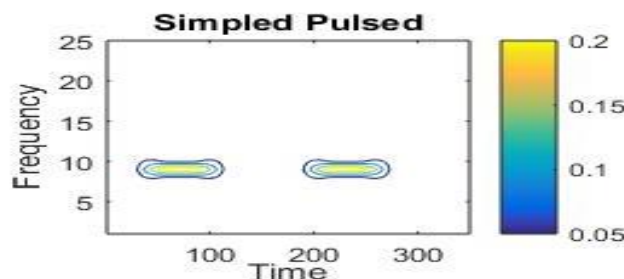
These three parts occurs by sliding of the window function for the duration of the window length specified. It is important to point out that Bartlett window (triangular) was used for spectrogram due to its high peak side lobe as compared to other basic window functions and hence its superiority and a moderate window length of 64 samples is used in order to avoid the smearing problem of spectrogram. An illustration of the 3D plot of all signals considered in this work is shown in Figure 1.3.



**Figure 1.3:** Time, frequency and power (3-D) plot of the simple pulsed radar signals using spectrogram.

Careful analysis of each plot in Figure 1.3, would indicate the characteristics of the simple radar signal. The simple pulsed has a constant time and frequency parameters, i.e. similar plot characteristics when viewed pictorially. Perhaps a better depiction of

the effect on spectrogram can be examined further if a 2D plot of only time and frequency is presented with the colored side bar representing the level of power. Figure 1.4 shows the plot of radar signals based on spectrogram analysis.



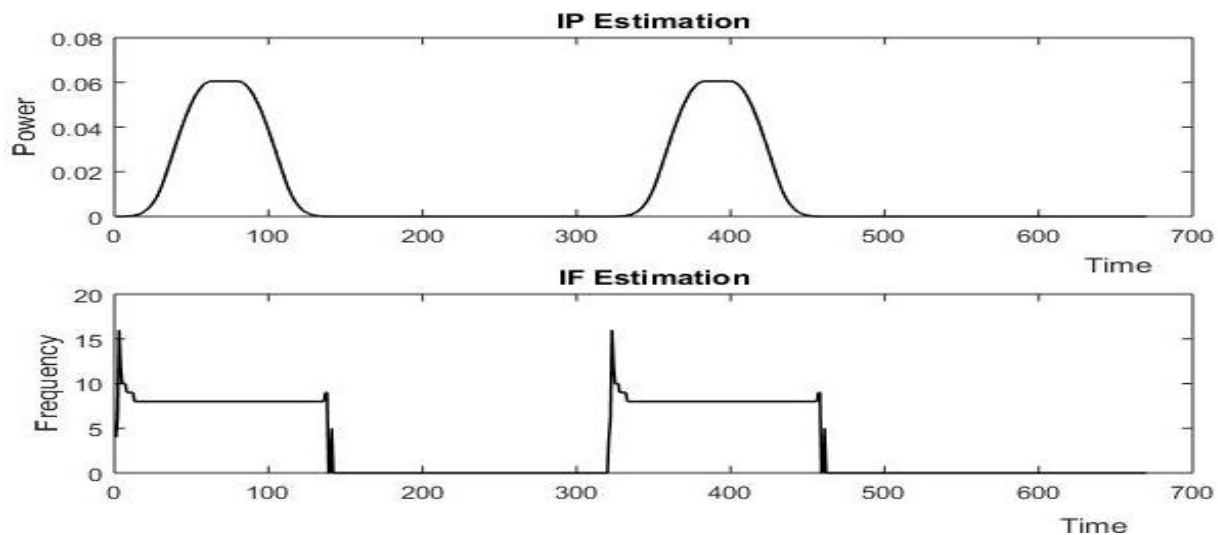
**Figure 1.4:** Time-frequency plots of a simple pulsed radar signal based on spectrogram analysis

Careful examination of each plot in figure 1.4 with the consideration of each circle level indicating carrier frequency value and space in between them representing PRI would show that the simple pulsed signal has constant carrier frequencies and constant PRI.

#### *Instantaneous Parameters Obtainment*

This part of estimation involves obtaining instantaneous power (IP) for time parameter estimation and instantaneous frequency (IF) for frequency parameter estimation from TFRs presented in figure in 1.3 and 1.4. Both of these parameters are

gotten at instants of time, where IP corresponds to max power based on the search along the frequency axis while IF corresponds to the frequency corresponding to the max power along this axis search. These steps are obtained by the combination of FOR loop to control the search and inbuilt MATLAB 'max' to find the maximum power. These estimations allow for conversion of output signal from the time-frequency analysis of 3D to 2D of power and time for IP and frequency and time for IF. A graphical depiction of these estimations is shown in Figure 1.5 for the case of simple pulsed signal.



**Figure 1.5:** IP and IF estimation for a simple pulsed rather signal.

It may be observed in figure 1.5 that the IP estimation depicts good time characteristics but cannot determine frequency characteristics and hence why the IF plots is used for frequency characteristics. The expansion in the IP estimation and spikes in the IF estimation are as a result of the estimation being an approximation gotten from the spectrogram TFD of a major shortcoming of uncertainty principle and not gotten directly. This observation also shows why there is need for threshold during estimation as noise further exaggerates this shortcoming. It is also stated that one may observe that IF estimation also demonstrates fairly good time characteristics

estimation but is not considered for time estimation as it was found to be of very poor estimation in the presence of noise in a pre-Monte Carlo simulation of this work.

#### *Time and Frequency Parameters Estimation*

As already stated, time parameters; PW, PRI1 and PRI2 are gotten from IP estimation of previous section. These parameters are gotten simply from a measuring algorithm formed from loop statements of 'FOR, IF and BREAK' statements based on a chosen threshold. Pulses of no sophisticated within pulse (intrapulse) modulation conventionally use half voltage points and half power points for pulse width

and spectrum width determination. However, eighth percentile threshold is used in this work in order to cater for a general and future research case of unconventional signals of frequency hopping and agile pulsed. The first part of this program deals with estimating delay of the incoming signal, and next part deals with PW estimation and with the remaining parts dealing the PRIs estimation. Origin point of each loop for any time parameter estimation is usually adjusted while the preceding parameters is obtained with allowance of few samples to cater for possible error that may arise. The frequency parameters; first

$$T = \frac{N_t}{F_s} \tag{1.1}$$

$$F_c = \frac{F_s}{N_s} N_f \tag{1.2}$$

Where:

$T$  is the time parameter in seconds,

$N_t$  is the time parameter in samples,

$F_s$  is the sampling frequency,

$F_c$  is the carrier frequency,

$N_s$  is the window length for TFD used (Spectrogram) and

$N_f$  is the frequency parameter in samples.

The time parameter cans either be PW or PRIs while the carrier frequency can be of the first or second pulse depending on the radar signal in view. Equation 1.1 depicts time parameter conversion for PW or PRI while equation 1.2 depicts frequency parameter conversion for any of the carrier frequencies.

$$SNR(dB) = 10 \log \frac{P_s}{P_n} \tag{1.3}$$

Where  $P_s$  the signal is power and  $P_n$  is the noise power. The noise model is additive white Gaussian noise obtained via the 'randn' command in MATLAB used for normally (i.e. Gaussian) distributed pseudorandom numbers. In this work, a simple algorithm is used to add noise to the signal by

$$P_n = \frac{P_s}{10^{\left(\frac{SNR}{10}\right)}} \tag{1.4}$$

Thereafter the noise is generated with its amplitude set to the noise power and added to the

and second carrier frequency are gotten from the IF simply by finding the average sample points at their corresponding obtained pulse duration time.

#### Time and Frequency Parameters Conversion

Finally, obtained parameters from the aforementioned analysis are converted back to microseconds in case of time parameters and Megahertz by the use of formula sets which relates samples to sample frequency. These formulas are presented below

### DISCUSSION OF RESULTS

Findings involving performance analysis of the methodology chosen in two forms; estimation, and comparing with previous work results. The discussion associated with the results is given alongside the results obtained. The estimation and performance are done through a Monte Carlo simulation setup whereby two loops involving controlling the signal-to-noise ratio (SNR) and iteration are used. A standard iteration of 100 loops for each SNR is used in this work while the formula used for the SNR (in decibel) is given below:

specification of the required SNR and generating the noise equivalent to the specified noise power of the SNR. Hence this noise power is gotten by making it the subject of the formula in equation 1.3 leading to the equation 1.4.

signal. It is important to point out that this noise is generated newly and hence randomly for each



iteration of each SNR. The signal parameters used for the performance analysis is selected based on the medium range radar, which is based on the literature presented by a leading author in the field of airborne radar (Stimson, 1998). The summary of this finding on

the relationship between PRF (the reciprocal of PRI) and range for X-band (military band) airborne radar is presented in the table below. However, it is important to point out that the category of PRF will depend on the operating conditions to a considerable extent.

**Table 1.2:** PRF Category (Stimson, 1998)

Category	PRF (kHz)	PRI (μs)	Range (Km)
Low	0.25 – 4	250 – 4000	37.5 – 600
Medium	10 - 20	50 – 100	7.5 - 15
High	100 – 300	3.33 – 10	0.5 - 1.5

The PRI was gotten by simply taking reciprocal of the PRF, while the range (unambiguous) is obtained dividing the speed of light with the product of PRF and two. The speed of light is used due to the

electromagnetic spectrum while the number two is to cater for the sending out and waiting for its echo of radar signals. As such, the table for the test radar signals used is shown in table 1.3.

**Table 1.3:** Test Radar Signals

S/No	Radar Signal Type	Time Parameters (μs)			Frequency Parameters (MHz)	
		PW	PRP1	PRP2	F1	F2
1	Simple Pulsed	1	40	40	10	10

PW of 1μs is used due to lack of sophisticated intra pulse modulation (like linear frequency and phase shift keying modulations), PRI of 40μs and 100μs corresponds to small and medium range of 6Km and 15Km respectively and carrier frequencies are selected within the Nyquist sampling theory (i.e. carrier frequencies must be less than or equal to half the sampling frequency to avoid aliasing). It should be recalled that a sampling frequency of 100MHz based on Agilent P-series meter as stated in scope of this

work is used. Estimation results based on these models are presented in subsequent sections

**ESTIMATION RESULTS AND DISCUSSION**

This section deals with estimation results, whereby probability of correct parameter estimation (POCPE) for each parameter of each signal is obtained after generation of test signals and addition of AWGN for SNR range of -18dB to 17dB. The POCPE is gotten from the equation 1.4:

$$POCPE (\%) = \frac{N_{CE}}{N_{TE}} * 100\% \tag{1.4}$$

Where  $N_{CE}$  is number of correct estimations of the parameter in consideration (may be any of time or frequency parameter to be estimated),  $N_{TE}$  is the number of total estimations, and in this work, equivalent to the standard number of iteration (i.e. 100). Therefore, the POCPE algorithm involves two

inputs; the estimations made during the Monte Carlo simulations for each SNR and the actual value of the parameter itself in order to match it and obtain the POCPE of that SNR. The obtained results for time parameters POCPE for all the test signals considered in tabular form is given below:

**Table 1. 4:** Monte Carlo Simulation Results for POCPE (Time)

SNR (dB)	Simple Pulsed (%)		
	PW	PRI1	PRI2
-18	10	0	0
-17	28	0	0
-16	71	0	0
<b>-15</b>	89	25	11
-14	99	90	69
<b>-13</b>	99	99	91
<b>-12</b>	<b>100</b>	<b>100</b>	97
-11	100	100	97
<b>-10</b>	<b>100</b>	<b>100</b>	<b>100</b>
-9	100	100	100
-8	100	100	100
-7	100	100	100
-6	100	100	100
-5	100	100	100
-4	100	100	100
-3	100	100	100
-2	100	100	100
-1	100	100	100
0	100	100	100
1	100	100	100
2	100	100	100
3	100	100	100
4	100	100	100
5	100	100	100
6	100	100	100
7	100	100	100
8	100	100	100
9	100	100	100
10	100	100	100
11	100	100	100
12	100	100	100
13	100	100	100
14	100	100	100
15	100	100	100
16	100	100	100
17	100	100	100

Two points that can be quickly noted from table 1. 4 is that different time parameters have POCPE of 100% at different SNR and that from a

certain SNR; POCPE of 100% is achieved irrespective of the time parameter in consideration. Two points can also be further deduced when the

table is closely examined; firstly, the POCPE of 100% for PW and PRI1 are the same compared to PRI2 for this signal considered; i.e. it is the same at SNR of -12 dB for PW and PRI1 and -10dB for PRI2. This replicate noise effect of practical scenario where the noise effect is higher as the signal gets longer.

Secondly, at SNR of -10 dB POCPE of 100% is attained for all time parameters and hence marks the optimum SNR for time parameter estimation using this methodology. Similarly, the obtained results for frequency parameters POCPE for all the test signals considered in tabular form is given below.

**Table 1.5:** Monte Carlo Simulation Results for POCPE (Frequency)

SNR (dB)	Simple Pulsed (%)	
	F1	F2
-18	33	2
-17	63	5
-16	90	1
-15	99	10
-14	<b>100</b>	38
-13	100	46
-12	100	52
-11	100	49
-10	100	68
-9	100	64
-8	100	66
-7	100	68
-6	100	86
-5	100	89
-4	100	86
-3	100	94
-2	100	93
-1	100	98
0	100	98
1	100	98
<b>2</b>	<b>100</b>	<b>100</b>
3	100	100
4	100	100
5	100	100
6	100	100
7	100	100
8	100	100
9	100	100
10	100	100
11	100	100
12	100	100
13	100	100
14	100	100

15	100	100
16	100	100
17	100	100

Similarly, just like for time parameters, two points that can be quickly noted from table 4.4 is that different frequency parameters have POCPE of 100% at different SNR and that from a certain SNR, POCPE of 100% is achieved irrespective of the frequency parameter estimation. Two points can also be deduced when the table is closely examined; firstly, the POCPE of 100% for carrier frequency of first pulse (F1) differs from that of second pulse (F2) for the signal considered; that is SNR difference of 16 dB (-14 dB for F1 and 2 dB for F2) for the simple pulsed radar signal. This also replicates noise effect of practical scenario where the noise effect is higher as the signal gets longer. Secondly, at SNR of 2dB, POCPE of 100% is attained for all frequency parameters irrespective of the signal in consideration, and hence marks the optimum SNR for frequency parameter estimation using this methodology.

## CONCLUSION

The spectrogram was the foundations for estimation of time and frequency parameters for analysis of time and frequency agility of radar signals. It can be generally concluded that optimum SNR required for frequency parameters estimation (2dB) is higher than that of time parameters estimation (-10dB) due to the basic signal processing fact that time parameters have more samples points compared to those of frequency parameter and hence have more resistance to noise compared to those of frequency parameters. Further researches will involve extending this method for other group of radar signals.

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