Modulation Classification of LPI Radar using Higher Order Statistics(HOS)

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***Abstract*— The main objective this paper is to detect the LPI radar signal using the Higher Order Statistics (Bispectrum) technique and automatically identify the type of modulation used. Normal spectral analysis techniques are failed to identify LPI signals in the noisy environment. QMFB, Wigner-ville techniques can detect the LPI signals but they unable to identify the modulation used in the signal and the phase of the signal is not preserved in these techniques. This paper reports the results of HOS technique (Bi-spectrum) applied to LPI radar signals. Various intra pulse modulations such as Barker signals, P1, P2, P3 and P4 poly phase coded signals are analyzed using HOSA technique to produce 2-D signatures of these signals. The results obtained clearly indicate the capability to automatically identify the type of LPI signal even with SNR as low as -3dB.**

Keywords—LPI Radar;HOS ; identify

I. INTRODUCTION

In the modern battlefield, radars face increasingly serious threats from Electronic attack and ARMs. An advanced feature of modern radar systems is, it has the capability "to see and not to be seen". Modern radars like Low Probability of Intercept radar has a powerful detection capability while simultaneously itself being not easily detected by electronic reconnaissance equipment.

LPI(Low Probability of Intercept) is the property of radar that because of its very low power, frequency variability,lower side-lobes, wide bandwidth and other design attributes makes its detection difficult by means of passive intercept receivers and ESM (Electronic Support Measure) systems [1]. These combined features prevent the LPI radar detection by modern intercept receivers. Many users of radar today are specifying LPI and LPID as important tactical requirements. Intercept receivers use different strategies to detect the radar based on carrier frequency, antenna scan rate, bandwidth, modulation period etc. Randomly varying of these parameters creates confusion to the intercept receivers [2]. Modern ESM (Electronic Support Measure) system is used for the detection of these LPI radar signals. ESM has to perform the task of detection, parameter identification and classification of these signals in a complex environment of high noise interference and multiple signals.

II. LPI RADAR WAVEFORM

LPI uses the continuous wave wide bandwidth signals. There are several LPI radar techniques available to the modern radar designer that may 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. This spread the radar's signal over a wide bandwidth and a period of time. The wideband CW techniques include [1]:

1. Barker Codes
2. Phase modulation (poly-phase codes)

1. Barker Codes

The binary phase-codes sequence of 0,π values that results in equal sidelobe after passage through the matched filter is called Barker code. The longest barker code is of length 13. When longer pulse compression is desired some of the pseudo random code is used. The peak side lobe levels of the linear recursive sequence and of barker codes greater than 5 are lower than -13.2 dB. However the sideobes of the Barker codes can be further lowered by employing a mismatched filter and accepting a slight loss in the peak signal-to-noise ratio. Table 1 shows the Barker codes for different lengths.

Table 1 Barker codes

Known Barker Codes of Length (L)		
L	Codes	
2	+1 -1	+1 -1
3	+1 +1 -1	
4	+1 -1 +1 +1	+1 -1 -1 -1
5	+1 +1 +1 -1 +1	
7	+1 +1 +1 -1 -1 +1 -1	
11	+1+1 +1 -1 -1 -1 +1 -1 -1 +1 -1	
13	+1 +1 +1 +1 +1 -1 -1 +1 +1 -1 +1 -1 +1	

Phase Shift Keying (PSK) continuous wave (CW) have recently been a topic of active investigation in LPI radar due to their wide bandwidth and low side lobes. Ploy-phase codes having lengths going into tens or hundreds of sub-codes are used to reduce the probability of interception.

A. *P1 Code*

Different phase codes are generated with different phases but with equal amplitude by varying the synchronous oscillator frequency. By placing the synchronous oscillator at the center frequency of the step chirp IF waveform and by sampling the base band waveform at the Nyquist rate, the poly-phase code called P1 may be obtained. The number of elements in p1 code isN^2.

If i is the number of the samples in a given frequencyandj is the number of the frequency, the phase of the j^{th}sample of the frequency is given by the equation

$$\emptyset_{i,j} = -\frac{\pi}{N}[N-(2j-1)][(j-1)N+(i-1)] \quad ......(1)$$

Where $i = 1,2,\dots,N$ and $j = 1,2,\dots,N$

An 8-phase P1 code of length 64 is considered in this paper.

B. *P2 Code*

P2 code is derived in the similar way as the P1 code is derived. Starting phase of P2 code is different but the phase increments in each group are same as that of P1 code. The P2 code also has a length or compression ratio of Nc=M*M. P2 code is valid only for even number of N, and each group of code is symmetric about 0 phases. The P2 code is given by

$$\emptyset_{i,j} = [2j-1-N][2i-1-N] \quad ....(2)$$

Where $i = 1,2,\dots,N$ and $j = 1,2,\dots,N$

P2 code has frequency symmetry as the P1 code and it also contain property of being palindromic code since the phases are symmetric in the center of the code.

In this paper 8-phase P2 code of length 64 is considered. Figure 2 shows the P2 signals.

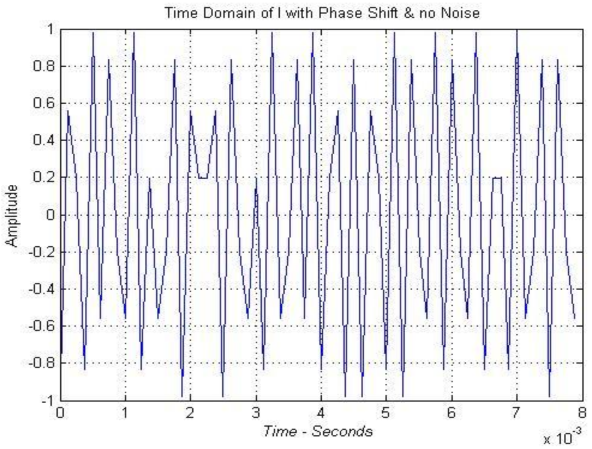

Figure 1 P2 signals

C. *P3 Code*

This code is derived by converting a linear frequency modulation waveform to base band using a local oscillator on one end of the frequency sweep and sampling the I and Q video at the Nyquist rate. If it is assumed that the waveform has a pulse width T in frequency f=f_0+kt where k is a constant, the bandwidth B of the signal will be approximately B=kT.

Assuming that the first sample of *I* and *Q* are taken at the leading edge of the waveform, the phases of successive samples taking t_c= (1/B) apart are,

$$\emptyset_i = \frac{\pi(i-1)^2}{N}, \text{ where } i = 1,2,\dots,N \quad ....(3)$$

D. *P4 Code*

The P4 code is conceptually derived from the same waveform as the P3 code. In this case the local oscillator is frequency is set equal to $f_0 + kT/2$ in the I-Q detectors. With this frequency, the phases of successive samples taking t_c apart are

$$\emptyset_i = \left[\frac{\pi(i-1)^2}{N}\right] - \pi(i-1), \quad \text{where} \quad i = 1,2,\dots,N \quad ....(4)$$

III. HIGHER ORDER STATISTICS

The LPI waveform data is processed by the Higher Order Spectral Analysis algorithm (Bispectrum) to modulationinformation from the input signal. This includes the use of Bi-spectrum technique [3]. All these techniques use 256 point FFT. The images (2D plots) produced by the above algorithms are unique for each LPI signal and serves a signature[6]. An experienced operator can also quickly identify the type of modulation code by looking at these plots

A. *Bispectrum Etimtion Usisng Direct class of Conventional Methods*

Let $\{x(1), x(2), \dots x(N)\}$be the available set of observationsfor Bispectrum estimation. Let us assume that f_s is the sampling frequency and $\Delta_0 = f_s/N_0$ is the required spacingbetween frequency samples in the Bispectrum domainalong horizontal or vertical directions. Thus $N_0$is the totalnumber of frequency samples.

1.Segment the data into K segments of M samples each, i.e., N = KM, and subtract the average value of each segment. If necessary, add zeros at each segment to obtain a convenient length M for the FFT.

2. Assuming that $\{x^{(i)}$ (k),k=0,1,2,…M-1} are the data of segment {i}, generate the DFT coefficients

$$F_x^{(i)}(\lambda) = \sum_{k=0}^{M-1} x^{(i)}(k) \exp\left\{-j\frac{2\pi}{M}k\lambda\right\}, ...(5)$$

$$\lambda = 0.1 \dots., M-1 \text{ and } i = 1,2,\dots,K$$

3) In general, $M = M_n \times N_n$, where M_n is a positive integer (assumed odd number), i.e., $M_n = 2J_n + 1$.In other words size of $M_n$determines the size of higher order spectrum smoothing over neighboring frequencies. Since M is evenand M_n is odd, we compromise on the value of N_n (closest integer). Estimate the nth-order moment spectrum, $\widehat{M}_n^{(i)}(\lambda_1, \dots \dots \lambda_{n-1})$, by frequency domain averaging

$$\widehat{M}_n^{(i)}(\lambda_1, \dots \dots \lambda_{n-1}) = \frac{1}{\Delta_n^{n-1}} \sum_{k_1=-J_n}^{J_n} \dots \sum_{k_{n-1}=-J_n}^{J_n} F_x^{(i)}(\lambda_1 + k_1) \dots F_x^{(i)^*}(\lambda_1 + \dots + \lambda_{n-1} + k_1 + \dots + k_{n-1}) *$$

$$F_x^{(i)}(\lambda_{n-1}+k_{n-1})i = 1,2,\dots,\mathrm{K}$$
……..(6)

$$\widehat{M}_n^{(i)}(\lambda_1,\dots\dots\lambda_{n-1}) = \frac{1}{\Delta_n^{n-1}}.F_x^{(i)}(\lambda_1)\dots F_x^{(i)}(\lambda_{n-1})$$
$$F_x^{(i)^*}(\lambda_1+\dots+\lambda_{n-1}), i = 1,2,\dots.k$$
…….(7)

For third order momentum n=3 i.e., Bispectrum

$$\widehat{M}_n^{(i)}(\lambda_1,\lambda_2) = \frac{1}{\Delta_0^2}F_x^{(i)}(\lambda_1).F_x^{(i)}(\lambda_2)F_x^{(i)}(\lambda_1+\lambda_2)\dots\dots..(8)$$

4) The nth order moment spectrum of the given data is the average over the K pieces

$$M_n^x(\omega_1,\dots,\omega_{n-1}) = \frac{1}{K}\sum_{i=1}^{K} M_n^{(i)}(\omega_1,\dots,\omega_{n-1}) \qquad \dots..(9)$$

Where $\omega_j \triangleq (2\pi\Delta_n)\lambda_j$,and $j = 1,2,\dots,n-1$

$$\widehat{M}_n^{(i)}(\omega_1,\omega_2) = \frac{1}{K}\sum_{i=1}^{K} M_3^{(i)}(\omega_1,\omega_2) \qquad \dots..(10)$$

IV. IMPLEMENTATION RESULTS

A. *GUI Implementation*

A GUI (Graphical User Interface) has been developed to analyze the LPI signals (at IF level of 160 MHz, Sampled at 500 MHz) of 10uS duration (5000 samples) generated from the Signal Source / samples generated through software.

The following signals are considered

1. Barker 5, 7, 13
2. P1, P2, P3, P4

For testing the algorithms of HOSA a large database of LPI waveforms is required. The waveform data Poly-phase codes P1, P2, P3, and P4 of length 64, carrier frequency 3000, sampling frequency 8000 and length of phase codes considered in this paper is 8.

Figure 2 shows the GUI.

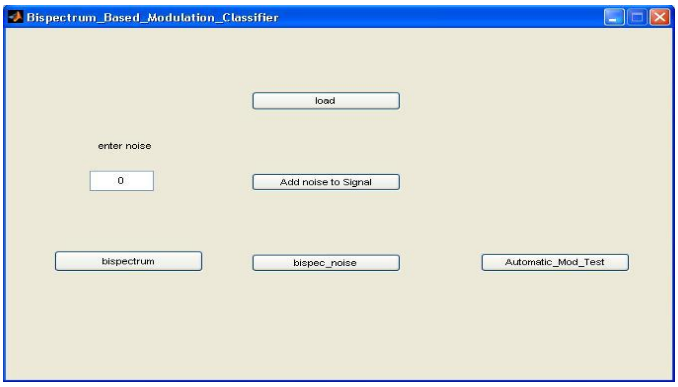

Fig 2 Graphical User Interface

From the output of the Bispectrum the received signal modulation is detected automatically by using the correlation coefficient. An experienced operator can detect the signals by looking at the plots, because the plots serves as a signature and unique for each modulation.

Figure 6 and 10 shows the Bi-spectra of P1and b7 signal.

It is observed that the uniqueness is maintained for all the signals even with SNRs of 15 dB and -3 dB to -6 dB and hence facilitates identification [5]. As an example, figures 7,8 shows the calculated Bi-spectra of p2 signal with SNRs of 0 dB and -6 dB respectively. Figure 9 shows the Bispectra of P4 modulation.

B. *Modulation Detection*

LPI signals use different poly phase modulations. In order to detect the type of modulation correlation technique is used. A set of reference signals are used for this technique which contains poly phase codes P1, P2, P3 and P4 and Barker codes of b7, b11 and b13.

Figure 4 and 5 shows the b13 and P1 reference signals.

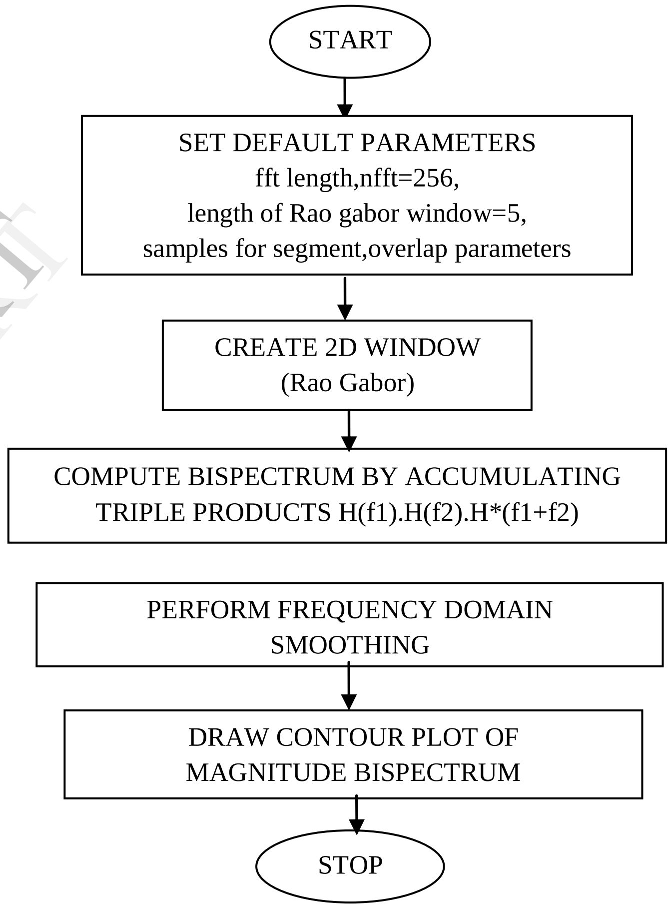

Fig 3 flow chart forcross correlation computation

Correlation coefficient is computed by cross correlating the Bispectrum signal with the different reference signals i.e., poly phase codes P1, P2, P3 and P4, Barker codes b5, b7, b13 and we get different correlation coefficient values for each modulation. The maximum value of correlation coefficient gives the particular modulation. By considering the maximum value of correlation coefficient it can able to detect the type of modulation used in the LPI signal automatically. Figure 11 shows the automatic detection of the modulation.

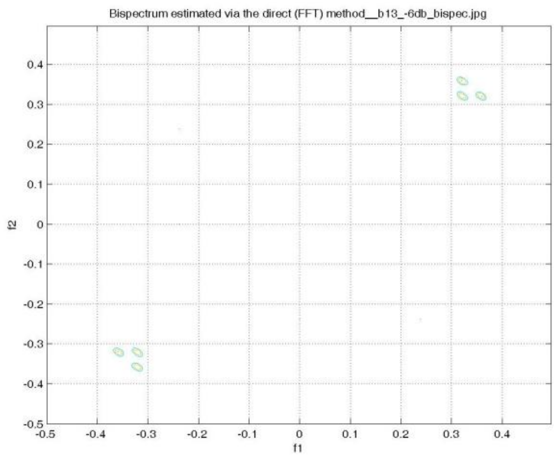

Fig 4 reference signal of b13 signal

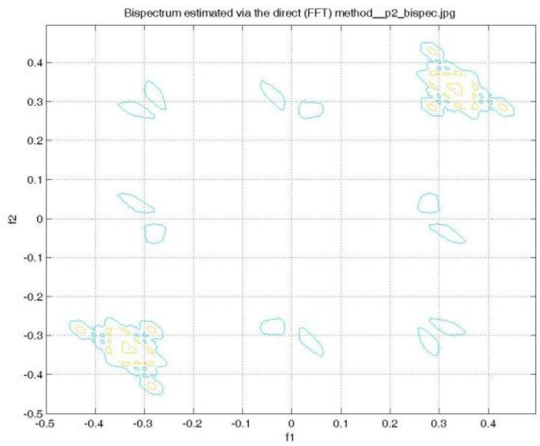

Fig 5 Reference signal of P2 signal

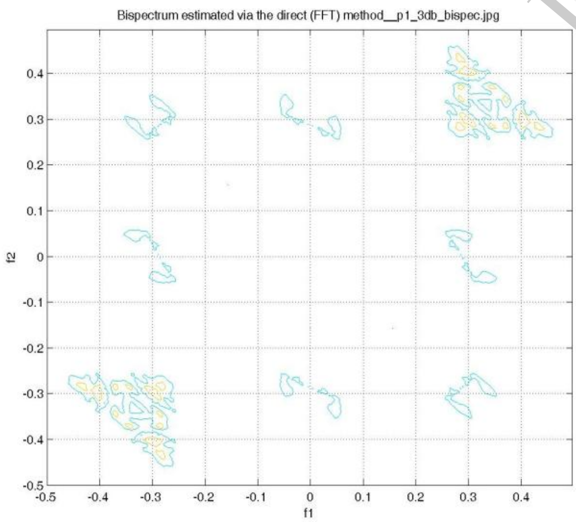

Fig 6 Bispectrum signal of P1 signal

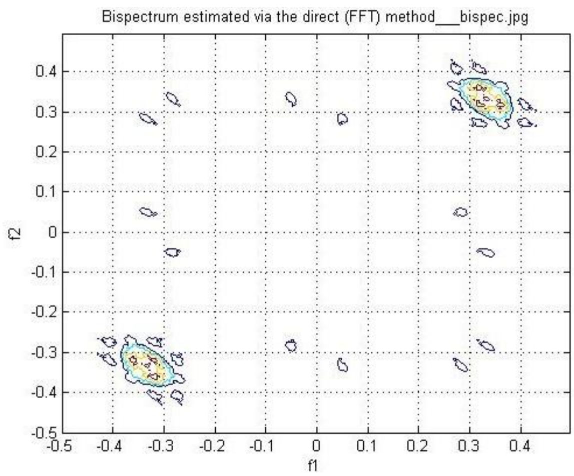

Fig 7 Bispectrum signal of P2 signal

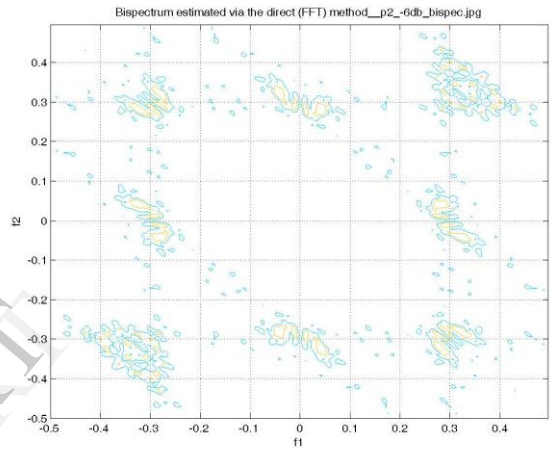

Fig 8Bispectrum signal of P2 signal SNR -6 dB

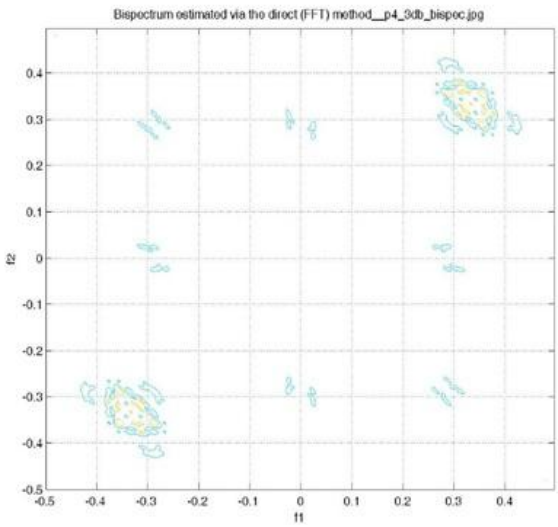

Fig 9 Bispectrum signal of P4 signal

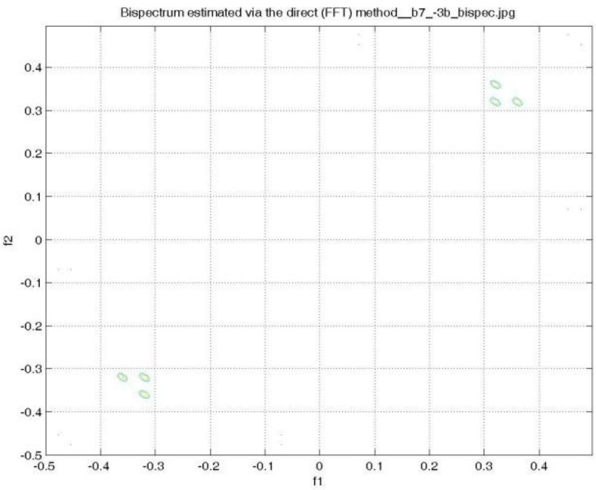

Fig 10 Bispectrum signal of b7 signal

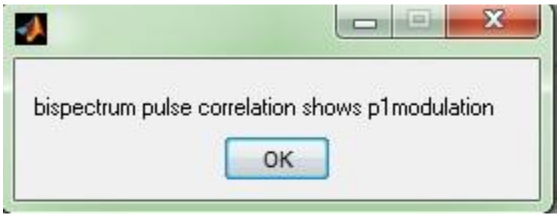

Fig 11 automatic detection of P7 modulation

V. CONCLUSION

Bi-spectrum techniques of LPI signal clearly demarcate one signal from the other even on addition of Gaussian noise. All the poly phase signals have distinct features in bi-spectrum contour plot. These features are quite visible even in the low SNR of 0dB. This system would be very efficient in detecting and classifying LPI radar signals automatically and it could be integrated in an ordinary Radar Warning Receivers (RWRs) to make them capable of detecting LPI signals.

Bi-spectrum gives the non- stationary information of the signal. With this feature, it can be applied to find unintentional modulations on pulse to characterize the radar hardware.

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