

# LPI RADAR SIGNAL GENERATION AND DETECTION

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**Abstract** - Low probability of intercept (LPI) is that property of an emitter that because of its low power, wide bandwidth, frequency variability, or other design attributes, makes it difficult to be detected or identified by means of passive intercept devices such as radar warning, electronic support and electronic intelligence receivers. In this paper, we present the properties and generation of some the important LPI waveforms based on Phase and Frequency modulation. The properties such as phase/frequency variation, auto-correlation function and the ambiguity function are shown for each waveform. These signals are then used to test with the help of signal processing technique that detects the waveform parameters of the intercepted signals. The technique is based on the use of parallel filter (sub-band) arrays and higher order statistics followed by image processing methods such as image threshold binarization and mathematical morphology to recognize and extract the shape of the radar signal even when the signal-to-noise ratio is -3dB.

**Key Words:** LPI radar, Ambiguity function, Higher order statistics, Adaptive threshold binarization, morphological processing. etc...

## 1. INTRODUCTION

Radar is the key sensor of any modern weapon system. Its capability to function in all weather environments at long ranges is unmatched with any available sensor. Radars are used for variety of tasks, ranging upward in size and complexity from man portable radars to ballistic missile tracking phased array radars. Increased reliance on radars has increased the importance of Electronic Warfare (EW). Electronic Support Measure (ESM) system, which is a division of electronic warfare, provides essential to the success of operation in the air combat environment. ESM deals with passive intercept of electromagnetic radiations from emitters like radars and analysis of the intercepted data to estimate the EW capabilities of the emitters. Passive intercept receivers such as Electronic Attack (EA), Anti Radiation Missiles (ARMs) and Electronic Warfare Support (ES) are the serious threats for the radar systems in the modern battlefield. To perform necessary tasks such as target detection and tracking and

simultaneously hide themselves from enemy attack, the modern radars are using the various techniques such as power management, wide operational bandwidth, frequency agility, antenna side lobe reduction, and advanced scan patterns (modulations). These types of radars are called Low Probability of Intercept (LPI) radars and they use techniques "to see and not to be seen" by modern and capable intercept receivers. This paper discusses the signal processing scheme capable of detecting and classifying LPI radar signals based on the combined use of parallel filter arrays, **Higher Order Statistics** (HOS) [3] and image processing techniques.

## 2. LPI RADAR SIGNALS

The conventional radars emit high energy pulses of short duration. However, the LPI radar transmitter makes use of long duration low power phase or frequency modulated signals that spread the signal bandwidth and making the signal hard to intercept [2]. Reducing the radar's peak effective radiated power (ERP) by using pulse compression technique is the most common in LPI radars. The receiver of LPI radar makes use of the appropriate matched filter so that the radar performance is similar to that of traditional pulsed radar radiating the same amount of average power. There are several LPI radar techniques available to the modern radar designer in various combinations, depending on the application. The objective is to spread the radar's signal over a wide bandwidth and a period of time.

### 2.1 Properties of LPI signals

The basic property required for LPI signals is large bandwidth. One of the widely used techniques to achieve large bandwidth in LPI radars is periodically modulated CW signals which have high range resolution characteristics. Wide bandwidth signals are preferably suited for pulse compression radar. In addition to low probability of intercept, two other significant design objectives, namely the high detection capability (requiring high energy content) and high range resolution (requiring short pulses/wide bandwidth) can successfully be met by the use of pulse compression techniques. To achieve good range resolution, pulse compression radars transmit low power and long duration intra pulse modulated waveforms. This modulation may be phase or frequency.

The desirable properties of LPI signals are that the peak sidelobe levels (PSL) and integrated sidelobe levels (ISL) in Autocorrelation Function (ACF), that is at the output of the matched filter must be low. It means while modulating the transmitted waveform, the order of the phase or frequency must be selected in such a way that magnitude of the sidelobes in autocorrelation function and Ambiguity Function (AF) must be very low. Low sidelobes at the output of matched filter shows the ability to detect even weak targets in presence of strong targets. If the ACF has high side lobes, a second nearby target might be able to hide in a sidelobe and go undetected.

### 3. GENERATION OF LPI WAVEFORMS

A signal generator toolbox was developed due to the necessity of creating the input signals with LPI characteristics. The purpose of the LPI signal generator toolbox is to generate a variety of LPI signals and evaluate their time-domain and frequency-domain characteristics. The program, implemented in MATLAB, can generate the following LPI signals.

1. Frequency Modulated Continuous Wave (FMCW)
2. Frank-coded signals
3. P3 codes
4. P4 codes
5. Costas-coded signal
6. Stepped frequency codes

#### 3.1.1 Frequency modulated continuous wave

Linear frequency modulation is a LPI radar technique and is readily compatible with solid-state transmitters. The most popular modulation is the triangular modulation of a Frequency Modulated Continuous Wave (FMCW). The linear FMCW emitter uses a continuous 100 % duty-cycle waveform so that both the target range and the Doppler information can be measured unambiguously while maintaining a low probability of intercept. The FMCW waveform shows excellent characteristics for the best use of the output power available from solid-state devices. This waveform is easier to implement than phase code modulation as long as there is not a strict demand on the linearity over the modulation bandwidth.

The triangular modulation consists of two linear frequency modulation sections with positive and negative slopes. With this configuration, the range and Doppler frequency of the detected target can be extracted unambiguously by taking the sum and the

difference of the two beat frequencies. These characteristics are shown in Figure 3.1.1.

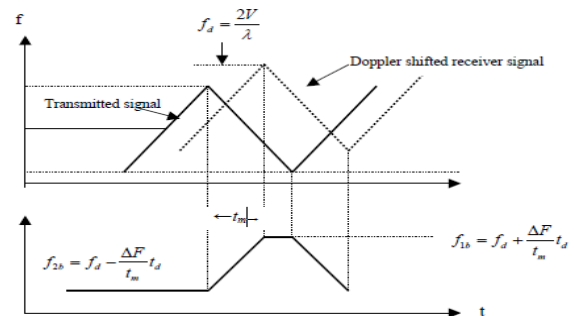


Figure 3.1.1 Linear frequency modulated triangular waveform and the Doppler shifted return signal.

For  $0 < t < t_m$ . The transmit signal is given by

$$s_1(t) = a_o \sin 2\pi \left[ \left( f_o - \frac{\Delta F}{2} \right) t + \frac{\Delta F}{2t_m} t^2 \right] \quad (3.1.1)$$

For  $0 < t < t_m$ . The transmitted base band signal is given by

$$s_2(t) = a_o \sin 2\pi \left[ \left( f_o + \frac{\Delta F}{2} \right) t - \frac{\Delta F}{2t_m} t^2 \right] \quad (3.1.2)$$

Figure 3.1.2 illustrates the triangular modulation signal for a FMCW signal with a modulation bandwidth of 250 Hz, modulation period of 50 ms and carrier frequency of 1000 Hz.

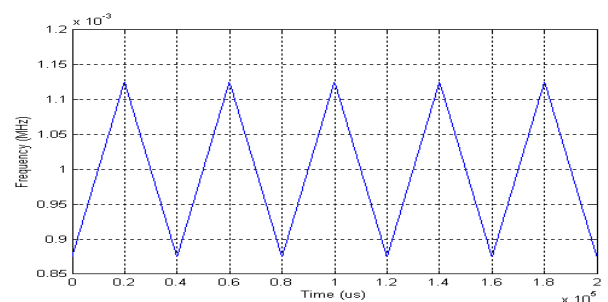


Figure 3.1.2 Triangular modulating signal for a FMCW

### 3.2 POLYPHASE CODES

Most widely used LPI signals in radar systems are the polyphase codes that may be efficiently implemented to provide large pulse compression ratios, with low peak side lobes. The advantages with polyphase waveforms are ability to achieve low side lobes and have good nonperiodic correlation properties. Some of the popular Polyphase codes such as Frank code, P3 code, and P4 codes are considered here in this paper. For each code, phase plot and ambiguity function are shown,

where as zero-cut in ambiguity function shows the autocorrelation function of the given sequence.

### 3.2.1 Frank Code

The Frank code belongs to the family of polyphase codes. This code has been successfully used in implementing LPI radar signals. A Frank-coded waveform consists of a constant amplitude signal whose carrier frequency is modulated by the phases of the Frank code. For each frequency or section of the step chirp having duration  $t_b$ , and phase group consisting of  $N$  phase samples that are obtained in the phases of  $N*N$ . The representation of a Frank-coded signal is given below.

$$\phi_{i,j} = \frac{2\pi}{N}(i-1)(j-1) \tag{3.2.1.1}$$

Where  $i=1, 2, \dots, N$  and  $j=1, 2, \dots, N$ . Each element of the Frank code is  $t_b$  seconds long. The phases of the Frank code may be generated for transmission by multiplying the elements of the given matrix.

$$\begin{bmatrix} 0 & 0 & 0 & \dots & 0 \\ 0 & 1 & 2 & \dots & (N-1) \\ 0 & 2 & 4 & \dots & 2(N-1) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & (N-1) & 2(N-1) & \dots & (N-1)^2 \end{bmatrix} \tag{3.2.1.2}$$

In radar applications, transmitters are operated in saturation; therefore, the abrupt phase transition can be made from one code element to the next. Figure 3.2.1.1 shows the phase plot of a Frank-coded signal for  $N=4$ .

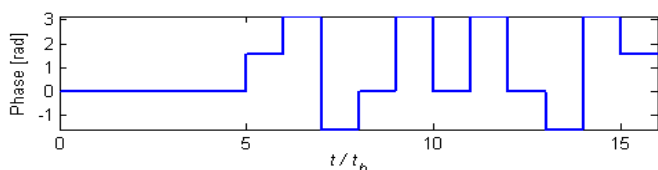


Figure 3.2.1.1 Phase plot of the frank-coded signal for  $N=4$ .

Figure 3.2.1.2 shows the ambiguity function of the frank code for  $N=4$ , where zero-cut is showing that it has good autocorrelation property.

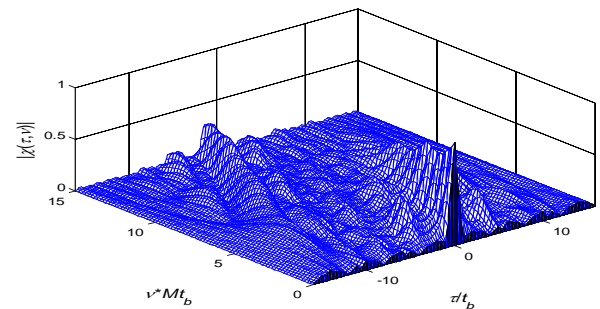


Figure 3.2.1.2 AF for a Frank-coded signal with  $N=16$

### 3.2.2. 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. The phases of successive samples are given by

$$\phi_i = \frac{\pi(i-1)^2}{BT} = \frac{\pi(i-1)^2}{N} \tag{3.2.2.1}$$

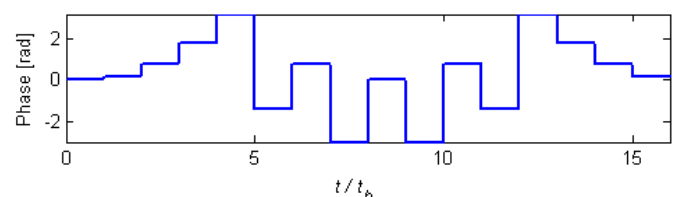


Figure 3.2.2.1 Phase plot for a P3-coded signal with  $N=16$ .

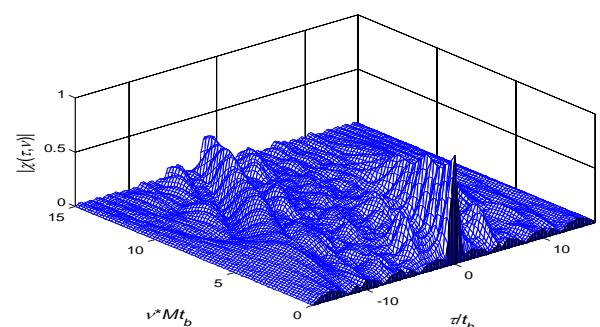


Figure 3.2.2.2 ambiguity function plot for p3-coded signal

### 3.2.3. P4 Code

The P4 code is conceptually derived from the same waveform as the P3 code. The phase values are given by the equation

$$\phi_i = \pi k(i-1)^2 t_c^2 - \pi k T(i-1) t_c = \left[ \frac{\pi(i-1)^2}{N} \right] - \pi(i-1). \quad (3.2.3.1)$$

Figure 3.2.3.1 showing the phase history of P4 code for the length N=16, and figure 3.2.3.2 shows the ambiguity function of P4 code for the sequence length N=16.

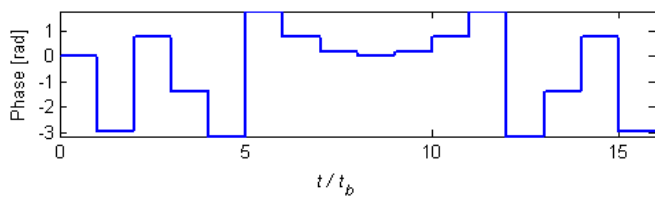


Figure 3.2.3.1 Phase plot for a P4-coded signal N=16

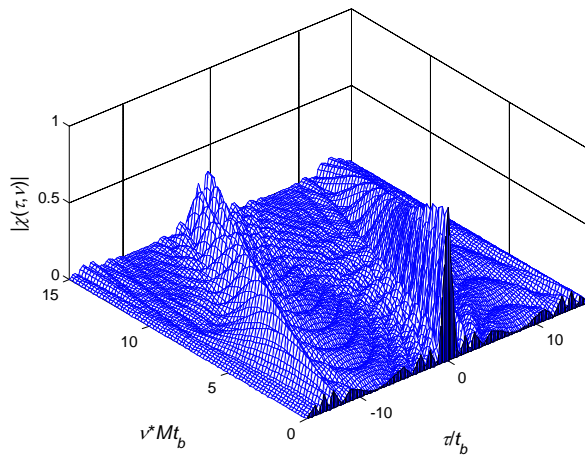


Figure 3.2.3.2 Ambiguity function of P4 code for N=16

### 3.3 Costas Code

Another class of LPI signals is frequency hopping. In this context, J P Costas shown that a “thumbtack” like

ambiguity function could be achieved with the proper selection of frequency hopped waveform having good range and Doppler resolution properties. A wide bandwidth can be achieved by using frequency-hopped sequences. In a frequency hopping system, the signal consists of one or more frequencies being chosen from a set  $(f_1, f_2, \dots, f_m)$  of available frequencies, for transmission at each of a set  $(t_1, t_2 \dots t_n)$ .  $(f_1, f_2 \dots f_m)$  is transmitted during each of the  $n$  equal duration time intervals  $(t_1, t_2, \dots t_n)$ . Such a signal is represented by a  $n \times n$  permutation matrix  $A$ , where the  $n$  rows correspond to the  $n$  frequencies, the  $n$  columns correspond to the  $n$  intervals, and the entry  $i, j$  equals 1 means transmission and 0 otherwise. This signifies that, at any given time, only one frequency is transmitted, and each frequency only once. The Costas frequency hopping sequence for the length  $N=7$  of order  $[4,7,1,6,5,2,3]$  is shown in figure 3.3.1 and its ambiguity function is shown in figure 3.3.2. one can clearly observe that Costas signal has high range-Doppler resolution.

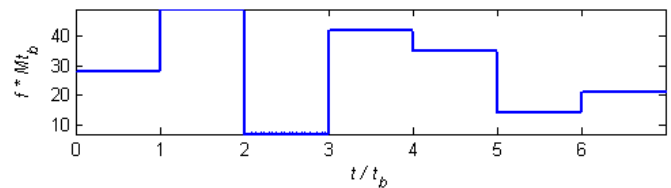


Figure 3.3.1 Frequency Hopping order of Costas Signal N=7

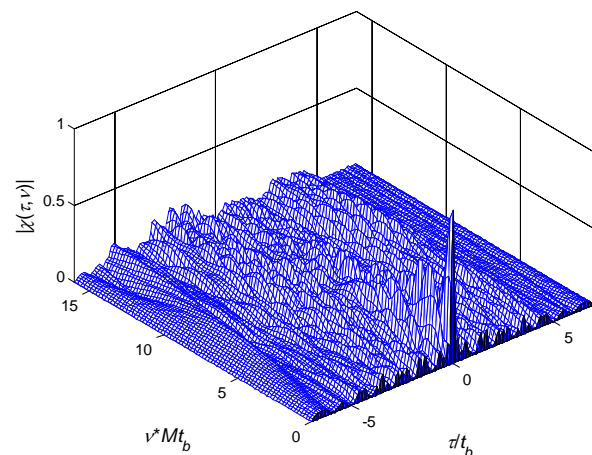


Figure 3.3.2 ambiguity function plot of Costas code

#### 4. DETECTION OF LPI RADARS

Detection and interception of LPI signals requires sophisticated receivers that use time frequency signal processing, correlation techniques and algorithms to overcome the processing advantage of the LPI radar. These signal processing algorithms require a large amount of computing speed and memory. Increasing the sensitivity of the receiver allows for detecting side lobes of the emitter, but at the same time obligates the receiver to process a significantly large number of signals. In addition to these challenges, new signal detection and feature extraction systems are needed to effectively analyze these new waveforms in a complex signal environment.

This paper deals with the detection of LPI signals using Parallel filter arrays and higher order statistics. Modern receivers must detect, intercept, analyze and classify signals in very complex environments with noise, interference and multiple signals present. Therefore, LPI radar signals are especially designed to complicate the detection process to obscure the radar operations.

This paper investigates a signal processing architecture based on the use of parallel filter arrays and HOS. A block diagram of this time-frequency approach is shown in Figure 4.1.

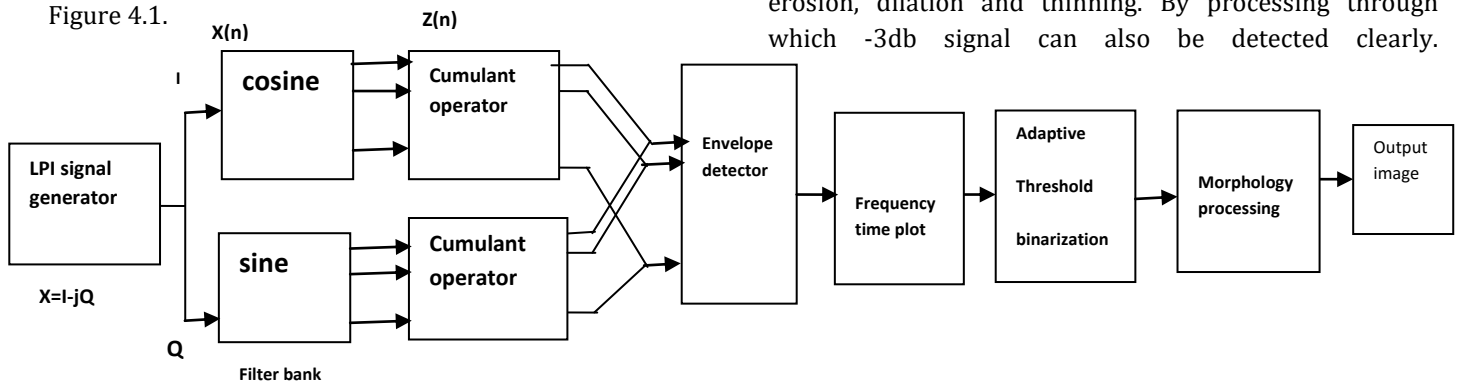


Figure 4.1 Overview of the proposed signal processing based on filter

#### 5. RESULTS

Results shown in figures 5.1 and 5.2, show that time-frequency images are clearly detected after applying the image processing techniques to the HOS filter outputs. In first stage, time-frequency image is converted into binary image by using adaptive threshold binarization algorithm. This binary image is further processed using morphological operations such as dilation, erosion and thinning. Figure 5.1(a) shows the time-frequency signal after higher order

In this case study, the detector consists of an array of filters followed by higher-order cumulant estimators, envelope detectors, adaptive threshold binarization and mathematical morphology.

The LPIG signal generator constructs an input file in the form of  $I$  and  $Q$ . The input signal  $x$  is obtained by finding  $x = I - jQ$ . The input signal is then zero-padded in order to prevent circular convolution when later multiplying by the FFT of the band pass filter. The filter bank decomposes the introduced signal into sub-band signals with narrow frequency bands. Therefore, this filter bank was designed as a sine and cosine bank considering the real and imaginary part of the complex-valued impulse response of each band pass filter. A third-order cumulant estimator (triple correlation) follows each sub-filter with the objectives of suppressing the additive Gaussian noise, extracting information due to deviations from Gaussianity and, at the same time, preserving the phase of the unknown signal. The outputs from each filter are given to image processing techniques like adaptive threshold binarization followed by morphological operations like erosion, dilation and thinning. By processing through which -3db signal can also be detected clearly.

filter having SNR=0dB and figure 5.1(b) shows the final output after applying image processing techniques to the output of HOS with 0dB SNR. Figure 5.2 (a) and (b) are showing the output of HOS and after applying threshold binarization and morphological operations when the signal-to-noise ratio is -3dB. It can be observed from the figure 5.2(a) and (b) that the signals which are not easily detectable after HOS, are detected clearly when morphological operations are applied.

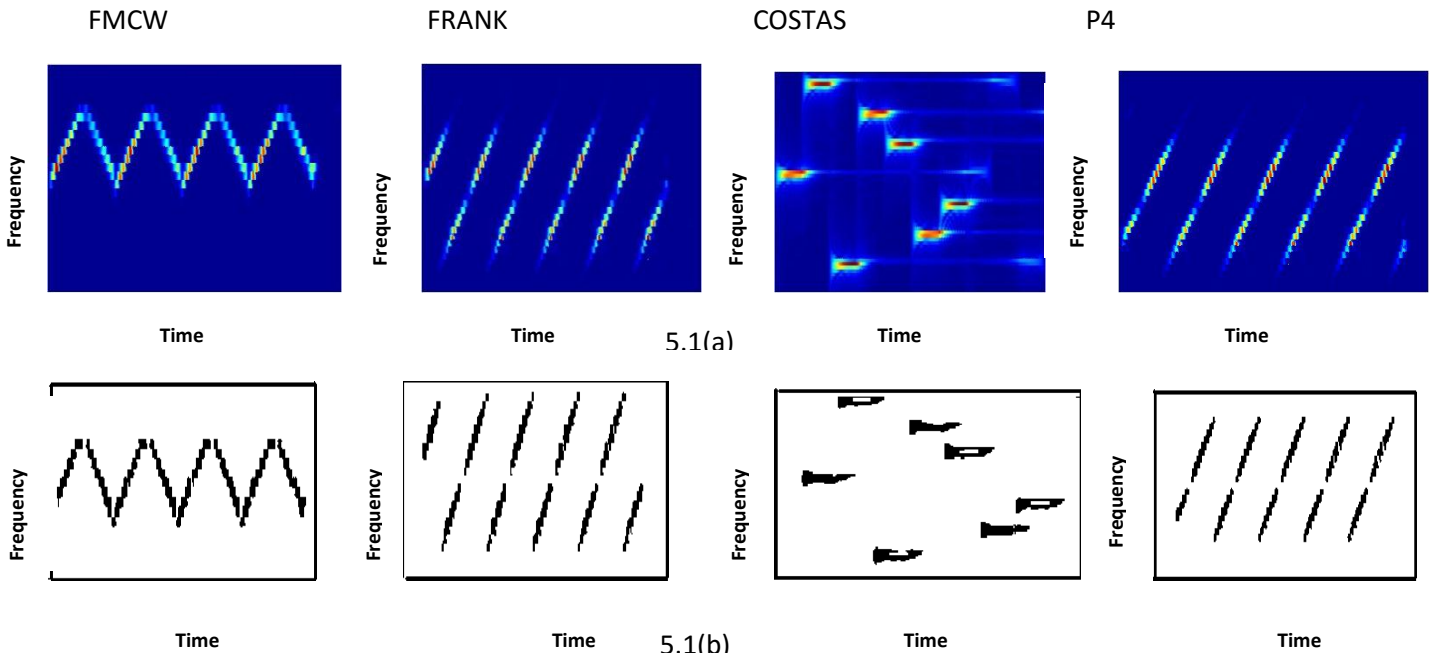


Figure 5.1 (a) Output of the HOS filter (b) Output after applying Binarization and Morphological operations for SNR=0dB

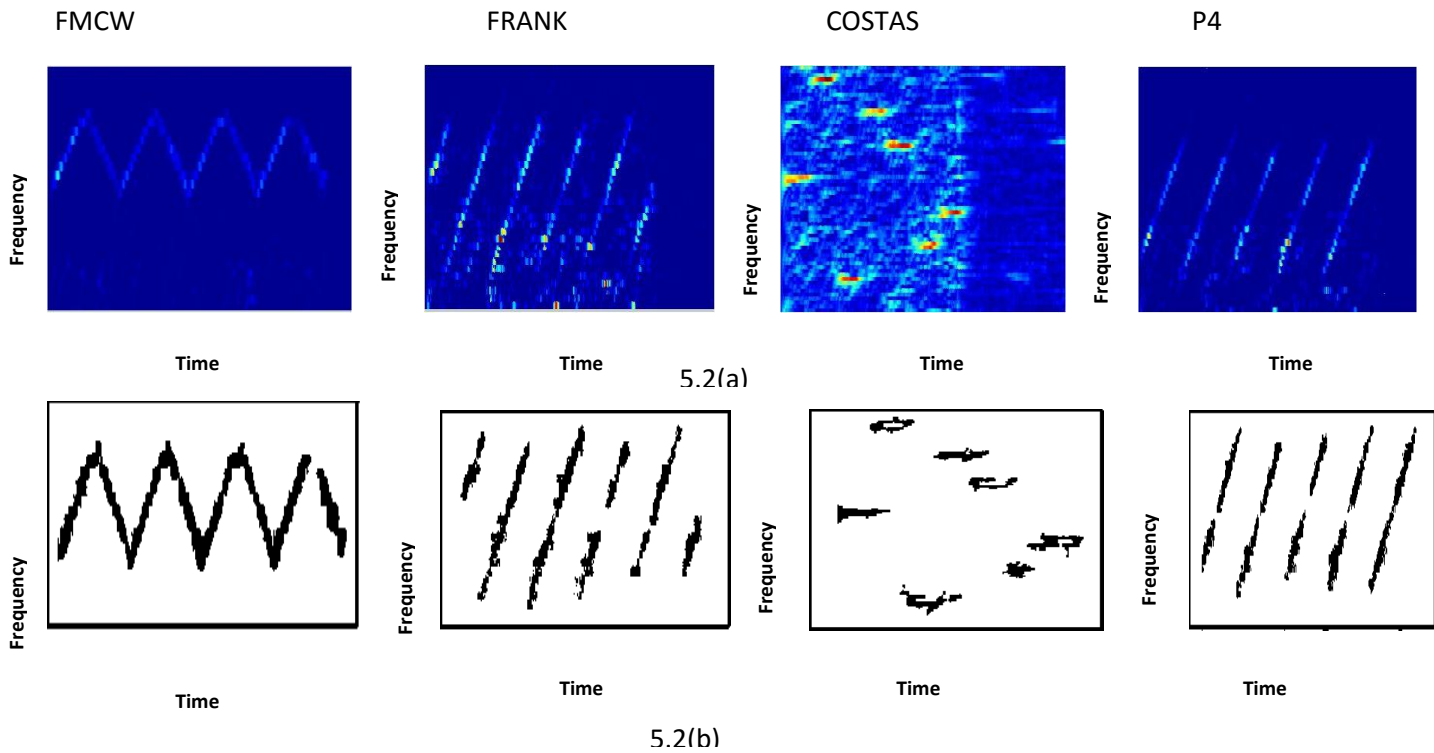


Figure 5.2 (a) Output of the HOS filter (b) Output after applying Binarization and Morphological operations for SNR= -3dB

## 6. CONCLUSION

The parallel array of filters can approximate the behavior of a matched filter. The purpose of this filter bank is to separate the observed signal into frequency bands. An increment in the number of filters in bank also increases the resolution of the system. The implementation of HOS, particularly third-order cumulant estimators, shows the potential of the method to suppress white Gaussian noise with increasing SNR.

This signal processing technique can efficiently, detect and identify the parameters of frequency coded waveforms such as FMCW and Costas signals. The detection and identification of frequency coded waveforms and Polyphase-coded signal is also satisfactory even at -3dB SNR environments. It can be concluded that combination of image processing techniques with HOS filtering can improve the detection and identification capability of the LPI radar system.

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