Interception FMCW radar using Wigner-Ville Distribution (WVD)

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ABSTRACT:
Using ESM, RWR and ARM missiles pose significant limitations to the performance of the radar systems in new battles. In these wars, MTI radars are commonly used with high Power to achieve long ranges, therefore they are easily detectable by the enemy EW receivers, and so they lose their effectiveness. In addition to having the ability of anti-Jamming and good ECCM, the radar systems should to use suitable CESM features to reduce the effectiveness of hostile ESM systems. So ability of low interception or LPI has become an important factor in radar systems. On the other hand, interception receivers must also develop detection capabilities and improve their performance in parallel to the LPI radars. The LPI radar signals are used in so many different waveforms and thus there are different ways to detection of these signals. In this paper, WVD and CWD techniques are used in order to detection FMCW signals (LPI signal).

KEYWORDS: Detection of LPI, Interception, Weiner-Ville Distribution and Choi-William Distribution.

1. INTRODUCTION

The radar is an abbreviation for RAdio Detection and Ranging expression. In general, the radar systems use modulated waveforms and directive antennas to transmit electromagnetic energy into a specific volume in space to search for targets. Objects (or targets) within a special search volume will reflect back to the radar a portion of this energy (radar returns or echoes). These echoes are processed by the radar receiver to extract target information such as range, velocity, angular position, and other target identifying characteristics [1].

Nowadays in modern warfare, radar systems are faced with very real threats, on the one hand Anti-radiation missiles (ARM) and on the other hand location radar and jammer systems. In other words, Using ESM, RWR and ARM missiles pose significant limitations to the performance of the radar systems in new battles. In these wars, MTI radars are commonly used with high Power to achieve long ranges, therefore they are easily detectable by the enemy EW receivers, and so they lose their effectiveness. In addition to having the ability of anti-Jamming and good ECCM, the radar systems should to use suitable CESM features to reduce the effectiveness of hostile ESM systems. So ability of low interception or LPI has become an important factor in radar systems. On the other hand, interception receivers must also develop detection capabilities and improve their performance in parallel to the LPI radars. The LPI radar signals are used in so many different waveforms [2], [3].

To hide from view of the enemy ESM receivers, or increasing LPI features, two general approaches have been proposed. One method has used of passive radar that has no radiation in radio environment, and other method is use of active LPI radar. Due to the inherent characteristics of passive radars, these are Bi-static and they need to have a copy of transmitter signals to detection targets. Also dimensions of these receivers are large because they transmit in VHF and UHF operating bands. Generally, these problems limit the use of passive radar in air surveillance radars. Due to do not encountered with these problems, the active LPI radars have greater popularity than passive radars. On the other hand the LPI radars use low transmits power, so for these the high-power transmitters do not require. This causes the LPI radars with low volume and cost, that this also adds to the popularity of the commercial radar [4].

1.1. Introduction to LPI radar

A low probability of intercept (LPI) radar is defined as radar that uses a special emitted waveform intended to prevent an intercept receiver from intercepting and detecting its emission. In other words, the ultimate goal of LPI radars is not-detection by the enemy. To achieve this objective, this system use power management, high bandwidth, frequency hopping, reducing antenna side lobe levels, and advanced scanning patterns. EW receivers use conventional techniques to detect of the LPI signal and identify of signal characteristics [4], [5].Electronic warfare and radar warning receivers usually use tow levels of LPI defined to reduce the Probability of detection and identification in receivers:

- **LPID Radar**: Low probability of identification (LPID) radar is defined as radar that uses a special emitted waveform intended to prevent an intercept receiver from intercepting and detecting its emission but if intercepted, makes identification of the emitted waveform modulation and its parameters difficult.
- **LPI Radar**: low probability of intercept (LPI) radar is defined as radar that uses a special emitted waveform intended to prevent an intercept receiver from intercepting and detecting its emission.

However, some references define LPID more comprehensive than LPI radar. According to the definitions above, an LPID radar is an LPI radar but and LPI radar is not necessarily an LPID radar.

However, on one side, LPI is related to performance of radar and the other is related to sensitivity of interception receiver. That may be a scenario in the face of ESM Receiver has feature of LPI but in other Receiver has not[4].

As mentioned in above, the radio frequency (RF) signal is inseparable component of battlefields. So the design and manufacture of receiver systems are most important issues in military. Tasks of the EW receivers are surveillance, detection and identification of signals that can be present in radio environment. An ideal receiver can receive signals in all frequencies with very good sensitivity, also be able to detect too weak signals in presence of strong signals. In addition, the receiver has a much small size, light weight and low consumption power [6].

LPI radars use the basic idea of the spread radiation in the time domain and frequency domain (that called broad signal) to achieve a power spectrum density below the noise level in interception receiver input. Detecting LPI signals need high signal processing gain. The gain of signal processing is usually obtained in digital signal processing as show in Fig.1 [6].

This paper examines the LPI signal detection technique using the Wigner-Ville Distribution (WVD). In Section 2 we introduce the signaling model required for LPI radar, the WVD technique for LPI signal detection and estimation are discussed in section 3. In Section 4 the simulation results for the receiver and radar are provided. Conclusions will be discussed in final section.

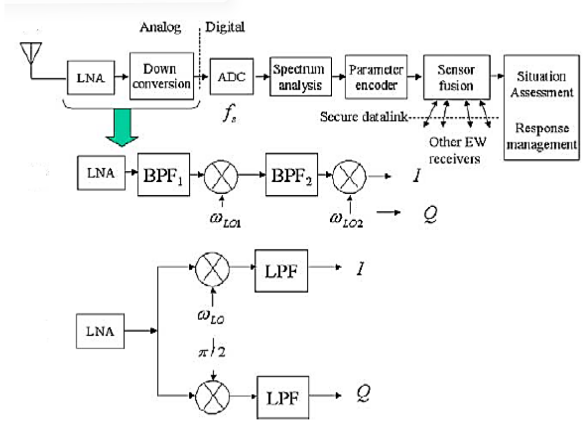

Fig. 1. Block diagram of (a) a wideband digital EW intercept receiver (b) two-stage heterodyne down conversion (c) homodyne down conversion

2. INTRODUCTION OF FMCW SIGNALS AND THEIR DETECTION BY RADAR

One of the posed issues in context of LPI radar is to choose suitable signals that can bring good performance for these systems. FMCW radar is kind of LPI family. In addition it is resistant to noise and deception jamming. The robustness of against noise jamming techniques in FMCW radars is often due to high bandwidth. The enemy systems should try to send signals with greater bandwidth than noise or work in Sweep mode. Working in Sweep mode is required to be sync with transmitter radar system. That is very difficult and if the process is successful, jammer system produce gated noise virtually. The robustness of the radar against these deception jammer techniques is because of synthesized signal, and it is almost impossible (It is hardly possible to estimate the signal parameters).

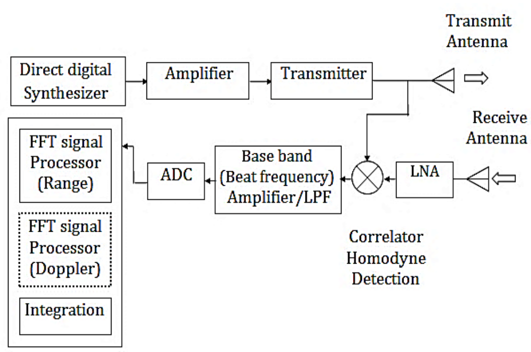

Fig. 2. Structure of FMCW radar system

FMCW radars can have a high bandwidth and resolution. The radar transmitter and receiver can have a simpler structure compared to the radar Phase Code and lower the cost, Because of its low instantaneous bandwidth. Because of the many advantages of FMCW radar, the most of valid companies design FMCW radars for military and commercial applications. The PILOT radar system can be named for example. A FMCW radar structure is observed in Fig. 2.

If a saw tooth waveform is used to transmit signals, we calculated the frequency difference between received and transmit signals, and with these results, we can calculate range of target. The frequency of the output of the mixer is obtained in Fig.3.

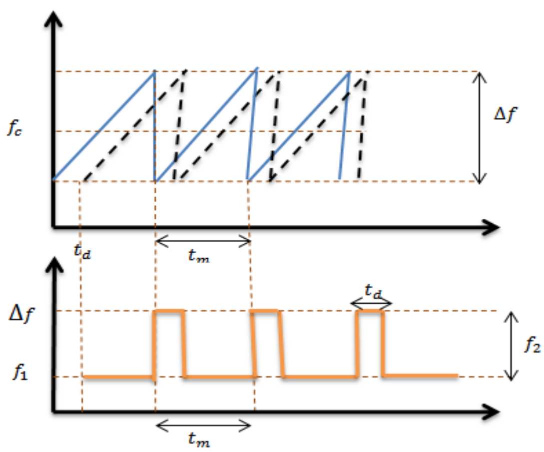

Fig. 3. Transmitter frequency, the receiver frequency and beat frequencies obtained from them

For this case, the sent waveform is:

$$x_T(t) = A\cos(w_c t + \alpha\phi(t)) = A\cos(w_c t + \frac{1}{2}\alpha t^2) \qquad (1)$$

Where A is the amplitude of transmitter signal, f_c is Carrier frequency and α is frequency slope. If width of modulation is equal Δf, and period is t_m, thus the frequency of transmission signal is:

$$f_T(t) = f_c + \frac{\Delta f}{T_m} t \qquad (2)$$

Frequency of the received waveform is given by:

$$f_R(t) = f_c + \frac{\Delta f}{T_m}(t - t_d) \qquad (3)$$

Where t_d is the delay time of returned signal. The radar uses the frequency difference between the transmitted frequency and the received frequency that the frequency beat is given in equation (4), and can be calculated distance of the target.

$$f_b = f_T(t) - f_R(t) = \frac{\Delta f}{T_m}\frac{2R}{c} \qquad (4)$$

In this equation, R is the distance of target from the radar, and c is the speed of light in free space. So FMCW radar can be done Metering due to have transmitter's frequency, but in the interception receiver there is no information of the transmitter signal [1], [8].

3. WIGNER-VILLE DISTRIBUTION

The WVD method has been used in many fields of engineering. These include optical implementations of the WVD, medical applications, image analysis, target detection, and the analysis LPI signals.

The WVD exhibits the highest signal energy concentration in the time-frequency plane for linearly modulated signals. The WVD contains interfering cross terms between every pair of signal components. Below, we begin with the definition of the WVD [8], [12].

3.1. Definition WVD

The WVD of a signal $x(t)$ is defined by [4]:

$$w_x(t,f) = \int_{-\infty}^{\infty} x\left(t + \frac{\tau}{2}\right) x^*\left(t - \frac{\tau}{2}\right) e^{-j2\pi f\tau} d\tau \qquad (5)$$

Where t is the time variable, f is the frequency variable, and $(\cdot)^*$ indicates a complex conjugate. The WVD is a three-dimensional function describing the amplitude of the signal as a function of time and frequency. These types of time-frequency distributions give a higher probability of detecting the modulation parameters. Some properties of the distribution below [12]:

- Wiener distribution of an arbitrary signal is always real.

$$w_x(t,w) = w_x^*(t,w) = \Re\{w_x(t,w)\} \qquad (6)$$

- By integrating the WVD of x in all over the time-frequency plane, we obtain the energy of *x*.

$$\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} w_x(t,w)\,dw\,dt = \int_{-\infty}^{+\infty} |x(t)|^2 dt = E_x \qquad (7)$$

- Shifting in the signal results to shift the WVD.

$$\tilde{x}(t) = x(t - t_0) \;\Rightarrow W_{\tilde{x}\tilde{x}}(t,w) = W_{xx}(t - t_0, w) \qquad (8)$$

- If the signal is zero within a certain time WVD also be zero.

$$x(t) = 0 \mid t_1 < t < t_2 \;\Rightarrow W_{XX}(t,w) = 0 \mid t_1 < t < t_2 \qquad (9)$$

The discrete WVD is defined as:

$$w_x(l,w) = 2\sum_{-\infty}^{\infty} x(l+n)x^*(l-n)e^{-j2wn} \quad (10)$$

Where L is a discrete time index from $-\infty$ to ∞. Equation (5) using the substitution $\tau' = \frac{\tau}{2}$ can be written as:

$$w_x(t,w) = 2\int_{-\infty}^{+\infty} x^*(t-\tau')x(t+\tau')e^{-j2w\tau'}d\tau' \quad (11)$$

Equation (10) is discrete version of Equation (11). Equation (10) shows frequency's variable is periodic with period π instead of 2π. The structure of this technique is showed in the Fig. 4.

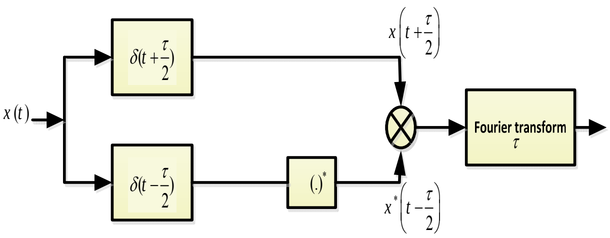

Fig. 4. Block diagram of WVD method

An example to show the excellent properties of the WVD analysis time – frequency is called chirp signal equal $x(t) = e^{(j2\pi kt^2)}$. Signal has frequency modulation (FM), instantaneous frequency that will change with time was defined in the previous section. In this case, the WVD will be equal to:

$$w_x(t,f) = \int_{-\infty}^{\infty} x\left(t+\frac{\tau}{2}\right)x^*\left(t-\frac{\tau}{2}\right)e^{-j2\pi f\tau}d\tau$$

$$= \int_{-\infty}^{+\infty} e^{j2\pi k\left(t+\frac{\tau}{2}\right)^2} e^{-j2\pi h\left(t-\frac{\tau}{2}\right)^2} e^{-j2\pi f\tau}d\tau \quad (12)$$

$$= \int_{-\infty}^{+\infty} e^{j4\pi kt\tau}e^{-j2\pi f\tau}d\tau = \delta(f-2kt)$$

If $k = \frac{1}{2}\alpha$, slope of the transmitter frequency is equal α. In this example, WVD method is shown for FM signals [12].

4. SIMULATION

In this section, we simulate WVD method and obtain output results for the four cases with different parameters. In the first case, we assume Chirp signal characteristics with $\Delta f = 500\text{Hz}$, Period $t_m = 1\text{ms}$ and center frequency $f_c = 1\text{kHz}$. The outputs of the WVD method with sampling frequency equal $f_s = 10\text{kHz}$ and without noise are shown in Fig.6 and Fig.7. Figure 5 shows the frequency changes over the time. The yellow box in Fig. 5 is time that signals are received. In Fig. 6, the amount of modulation width is equal $\Delta f = 500\text{Hz}$, and period of signal is one millisecond. Also in Fig.7, the center frequency is $f_c = 1\text{kHz}$ that it is accepted with a little error.

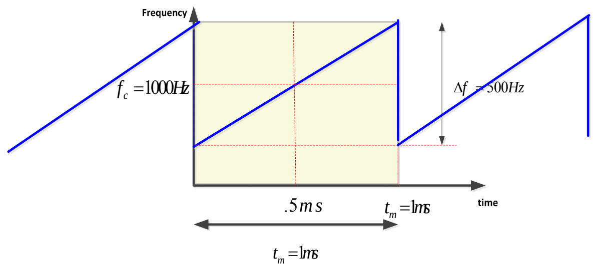

Fig. 5. In the first case, a Complete Sweep is received

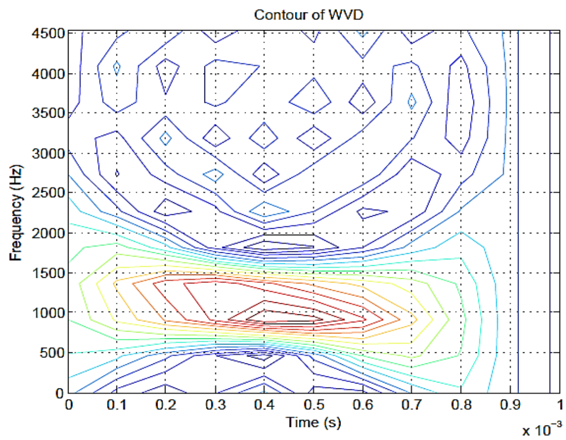

Fig. 6. Output of WVD method (time-frequency) for the first case

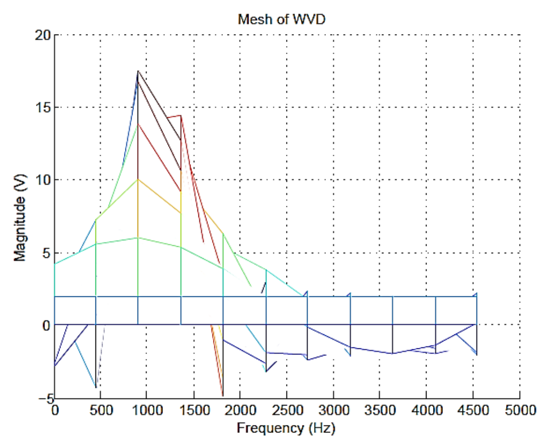

Fig. 7. Output of the WVD method (magnitude-frequency) for the first case

For the second case according fig. 8, we assume that a fracture is created in received signal. In this case, the first chirp has these parameters $\Delta f_1 = 500\text{Hz}$, period $t_{m_1} = 1\text{ms}$ and center frequency $f_{c_1} = 1\text{kHz}$, and in the second chirp, the parameters are $\Delta f_2 = 500\text{Hz}$, $t_{m_2} = 1\text{ms}$ and $f_{c_2} = 1\text{kHz}$. The output of the WVD method with sampling frequency $f_s = 10\text{kHz}$ and without noise is shown in Fig.9 and Fig.10. The receiver has received signal in only second half chirp of the first signal and the first half of the second signal.

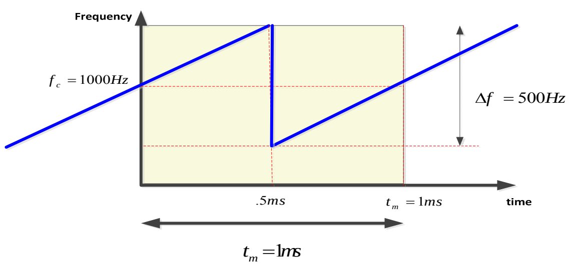

Fig. 8. The received signal for the second case

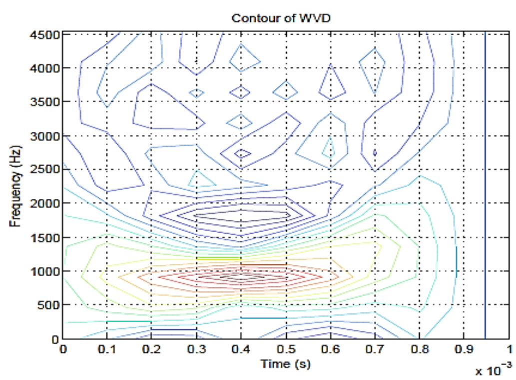

Fig. 9. Output of WVD method (time-frequency) for the second case

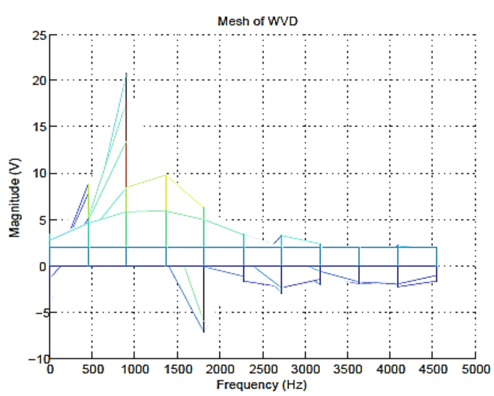

Fig. 10. Output of the WVD method (magnitude-frequency) for the second case

Figure 8 shows the changes of frequency over the time. In this figure, the chirp slope is the same for both of received signal. The yellow box in Fig. 14 is time that signals are received. In Fig. 9 the amount of modulation width is $\Delta f = 500\text{Hz}$ and period is one millisecond. Also in Fig.10, a center frequency is equal to $f_c = 1\text{kHz}$, that is accepted with little error. The comparison of Fig.10 with the Fig.7, and Fig.9 with Fig.6, we can conclude that the parameters of signal are obtained if the signal characteristic does not change in two parts of received signal, and fracture of the reception signal will not affect in the detection performance.

In the third case, we assume that the fracture is created. In this case, the first chirp has these parameters $\Delta f_1 = 500\text{Hz}$, period $t_{m_1} = 1\text{ms}$ and center frequency is $f_{c_1} = 1\text{kHz}$. In The second chirp, the parameters are $\Delta f_2 = 1\text{kHz}$, $t_{m_2} = 1\text{ms}$ and $f_{c_2} = 1\text{kHz}$. The outputs of the WVD method for this step with sampling frequency equal $f_s = 10\text{kHz}$ and without noise are shown in Fig.12 and Fig.13. In this case, receiver has received only second half chirp of the first signal and the first half of the second signal and $\Delta f_2 = 2\Delta f_1$.

Figure 11 shows the frequency changes over the time. In this figure, the chirp slope is not the same in two parts of received signal. First chirp slope has twice other chirp. The yellow box in Fig. 14 is time that signals are received. In Fig.12 the amount of modulation width and period are not detected. But in Fig.13, a center frequency can be seen equal $f_c = 1\text{kHz}$ that it accepted with little error. The comparison of this case with the previous case, we can conclude that if both part of received signal have the same information, we can obtain parameters of signals with WVD method. The center frequency of the third mode in Fig. 12 and Fig. 13 is visible due to participate features in both of signals. However, other parameters are invisible due to differences in the value. The period is the same for both but it is invisible because Chirp slope depends on two parameters, width of modulation and period therefore different in any parameters cause these parameters are invisible in output of WVD method.

In the fourth case we assume that a fracture is created. Also we presume that a frequency hopping mode is occurred. In this case, the first chirp has parameters $\Delta f_1 = 500\text{Hz}$, period $t_{m_1} = 1\text{ms}$ and center frequency $f_{c_1} = 1\text{kHz}$. In The second chirp, the parameters are $\Delta f_2 = 500\text{Hz}$, $t_{m_2} = 1\text{ms}$ and $f_{c_2} = 2\text{kHz}$. The outputs of the WVD method with sampling frequency $f_s = 10\text{kHz}$ and without noise are shown in Fig. 15 and Fig. 16.

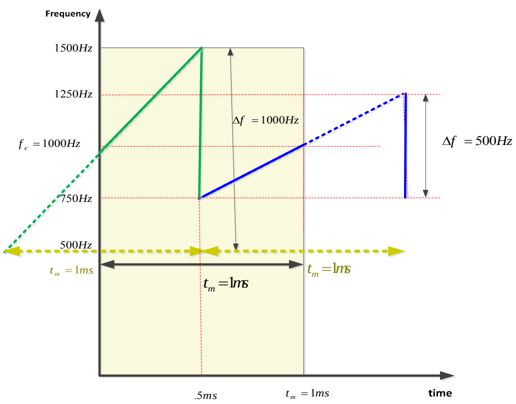

Fig. 11. the received signal for the third case

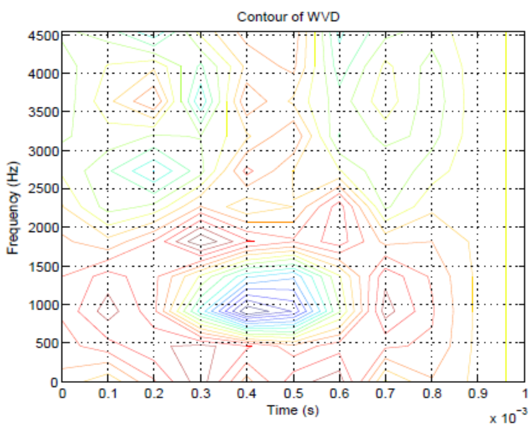

Fig. 12. Output of WVD method (time-frequency) for the third case

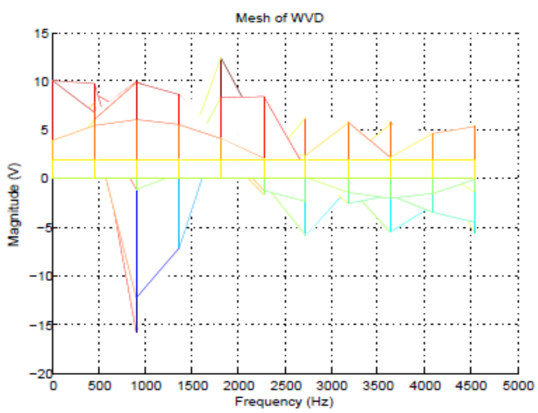

Fig. 13. Output of the WVD method (magnitude-frequency) for the third case

Figure 14 shows the frequency changes over the time. As you can see in this figure, the chirp slope is equal in two received signals. First chirp's center frequency is twice other received signal. The yellow box in Fig. 14 is time that signals are received. In Fig. 15, output of WVD method in frequency and time is plotted. According this, width and period of signal are obtained and is equal to 0.5millisecond. But from Fig.16, the center frequency is obtained $f_c = 1.5\text{kHz}$, but it should be noted that this is not true for the frequency real value, and it is called cross term. From comparison of this case with the previous case, we can conclude that if both have the same information, we can obtain transmitted signal characteristics with WVD method. In Fig.15 and Fig.16, modulation width for the fourth case is visible due to participate in both. However, other parameters are invisible due to differences in the values.

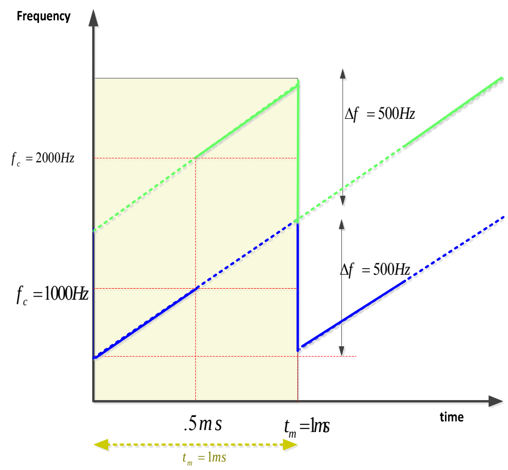

Fig. 14. The received signal for the fourth case

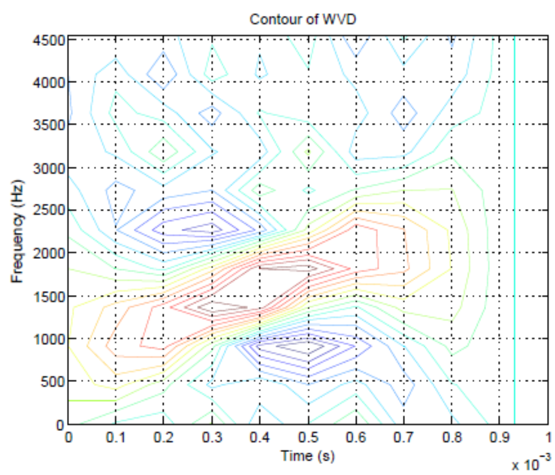

Fig. 15. Output of WVD method (time-frequency) for the fourth case

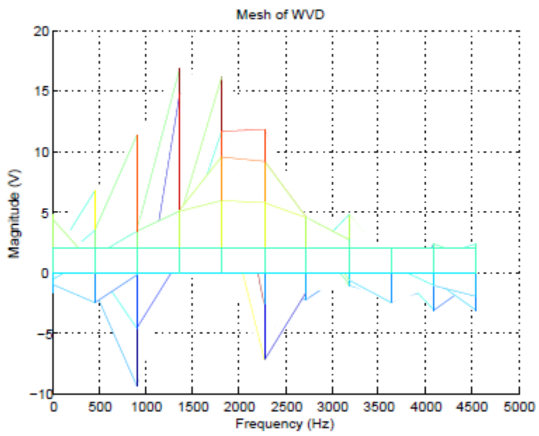

Fig. 16. Output of the WVD method (magnitude-frequency) for the fourth case

5. CONCLUSION

To stay hidden from the eyes of the enemy ESM receivers, or increasing LPI feature, two general approaches have been proposed. One method is using the passive radar that has no radiation in radio environment, and other method is using the LPI active radars. In general, the passive radar systems are used in air surveillance radars only. Unlike other conventional systems, LPI radar systems use of low power transmission, and do not require high-power transmitters. This feature makes the LPI radar systems have smaller size and cheaper prices. Also commercial radar's popularity is increasing because of these characteristics. The FMCW signal is one of the most commonly used signals in LPI radar. Because of the many advantages of FMCW radar, the most of valid companies design FMCW radars for military and commercial applications. The PILOT radar system can be named for example. In this paper, WVD method is used for detection and estimation of LPI signal, as you can see in the simulation results. WVD method can be used correctly for detection FMCW signal and estimate its parameters. But when we have frequency agility signals, these techniques can't correctly estimate the central frequency. In fact, if the first signal and the second signal have the same information, the signal parameters can be estimate correctly with this method.

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