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Zero Crossing Counter for Accuracy Improvement of FMCW Range Detection

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Abstract

For civil and military purposes FMCW radars are widely used. The theoretical background is well-established. Nevertheless, improvement of various aspects of these radars is still required. Signal processing is one of the crucial points of the system which determines the capabilities of the radar. In this study a zero crossing detector implementation, which can be efficiently used for target detection and range calculation in short range FMCW range detector is proposed. The duration between consecutive zero-crossings are used as the data instead of the number of cycles per unit time. Experimental evaluation of its performance is also given.

1. Introduction

FMCW radars are being used for many civil and military applications including smart ammunition sensors, vehicle collision avoidance and industrial control [1]. Specifically, the short range applications can be listed but not limited to the followings: collision avoidance, proximity fuse, level measuring of liquid tanks and hidden object detection. The main advantages of the FMCW radars for such applications are due to their ability to measure very small ranges with small range errors. Light weight, low energy consumption and the compactness of the circuitry are additional advantages [2].

The signal processing can be done either in frequency domain or in the time domain. The most widely used frequency domain methods are FFT based. There are works on reducing the computational load of FFT processing [3] and increasing the range resolution [4] and accuracy [5]. Besides FFT, some novel methods of parameter estimation for moving targets are present [6]. In addition, the high-resolution spectral estimation methods such as MUSIC, AR, ARMA and neural network algorithm are also used for FMCW radars [7-10]. All these methods have a trade off between computational load and range measurement improvement. The methods analyzing the signal in time domain is mainly based on discrimination by zero crossing. In the early years in which spectral methods were popular for FMCW signal processing, there had been works about the time domain analysis and the comparison of two methods [11-12].

All the mentioned method implementations are capable of discrimination of multiple targets and have complex circuitry. Nevertheless, for a low cost system, the signal-processing unit should be compatible with the simple circuit structure and compactness of the radar. In the applications that require the range information of a specific target such as level gauging, radio altimeter etc. FMCW range detectors with zero crossing counters can be used. The simple circuitry and low cost implementations as compared to other signal processing unit implementations will be the benefits of this choice. Various ZCC implementations are possible. In this study, a zero-crossing counter with improved range accuracy is suggested. While preserving the simple and low cost implementation, our ZCC is better in range accuracy than the conventional cycle counters, which are used for FMCW range detectors [12].

In the following sections, firstly, the basic FMCW principle is given and then ZCC implementation is discussed. After that, range accuracy calculations are given for a general cycle counter and for our ZCC implementation. Finally, the experimental setup and measurement results are given, for discussing the ZCC performance analysis.

2. Basic FMCW Principle

In FMCW radars, the frequency difference between the frequency modulated transmitted signal and the received echo signal is measured, and named as the beat frequency. Beat frequency is a direct measure of the range for linearly increasing frequency. In practice, the linear increase of frequency is realized by triangular frequency modulation, which results in distortions in the beat signal. Figure 1 shows the signals for triangular modulation and the corresponding beat frequency f_b.

The range and the beat frequency relation can be obtained by simple trigonometric relations and using the fact that time delay is $T = 2R/c$, as follows:

$$f_b = T \cdot m_f = \frac{2R}{c} \cdot m_f \tag{1}$$

where m_f is the slope of the frequency change and:

$$m_f = \frac{\Delta f}{1/2f_m} = 2f_m \Delta f \tag{2}$$

Using (1) and (2)

$$R = \frac{c}{4f_m \Delta f} \cdot f_b \tag{3}$$

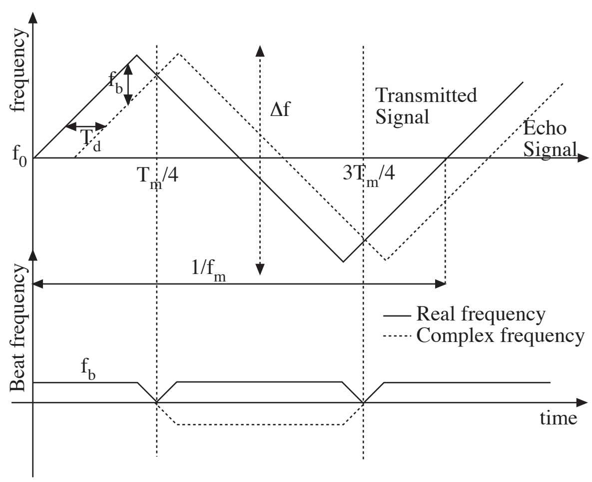


Figure 1. Triangular modulated FMCW signals and corresponding beat frequency.

As seen in (3) measuring the beat frequency, range is directly obtained from known parameters: frequency deviation Δf, modulation frequency f_m and speed of light c. The widely used method to determine the beat frequency is the application of FFT. There are two main restrictions in its application. The first one is the comparatively complex system structure and the second and the more important one is the distorted signal spectrum due to the non-ideal properties of the received signal. A sample measured spectrum of IF signal is given in Figure 2. The time domain response of the same signal observed on the oscilloscope is given in Figure 3. On the same figure, the correspondence between the transmitted signal, beat frequency and measured IF signal are shown. The experimental set-up is the one that is used for the measurements reported in Section 4.

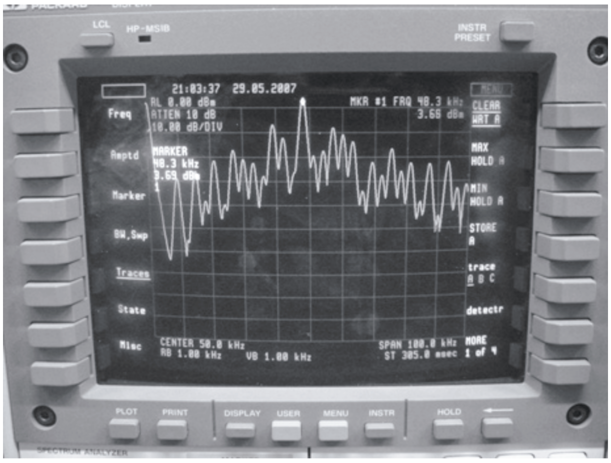


Figure 2. Sample spectrum observed in HP 70004 Spectrum Analyzer.

Although there are spurious frequency contents in the spectrum, indeed, it is a very clean spectrum to measure the beat frequency. In most cases, spurious content may have relatively high power levels. Compensation circuitry can be designed and used to improve the response. However, it is also possible to improve the range accuracy without complicating the circuitry.

3. ZCC Implementation and Range Accuracy

In the presented ZCC, the main concern was implementing it with the commercial off the shelf components, with low cost and small size. The implemented ZCC block diagram is given in Figure 4. National Semiconductor high-speed comparator LM319 is used to generate square wave as the counting signal. The comparator part is designed to have adjustable threshold level to be able to suppress the noise present with the IF signal. For short range applications the signal is strong and SNR (Signal-to-Noise Ratio) is high, making the zero crossing counting more accurate for the beat frequency determination. For the FFT approach, the measurement of low beat frequencies corresponding to short ranges is difficult due to the amplitude and phase noise leaking into the IF stage of the radar. On the other hand, this leakage does not create that much problem to the ZCC detector.

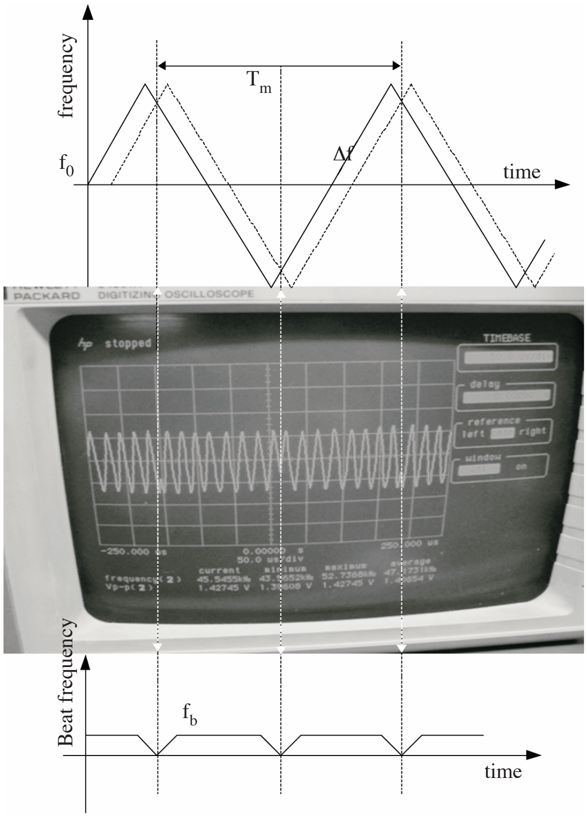


Figure 3. Measured time domain IF signal (HP Digitizing Scope 54501).

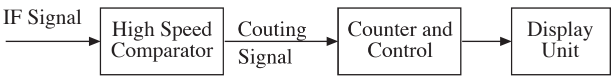


Figure 4. ZCC block diagram.

Microchip 8-bit CMOS microcontroller PIC 16f877 is used as the counter and control unit due to availability of the component and the ability to add the future functionalities to the detector. Averaging the detected beat frequency or giving the mean/median value of a set of readings to have more stable measurements, or using look up tables to increase the range resolution further are some of the applicable functionalities.

The output of the comparator is connected to the capture/compare input of the PIC 16f877. The capture/compare interrupt enabled at the rising edge of the counting signal coming from the comparator and timer register content is buffered to calculate the time until next rising edge where another interrupt is enabled. To measure an averaged frequency capture interrupt can be configured to be enabled at every fourth rising edge. A further averaging is done for the last three reading of the frequency measurement. The resultant frequency measurement is displayed on a 2x16 alphanumeric liquid crystal display (LCD). The control of the LCD display is also done by PIC 16f877.

The theoretical limit with which distance can be measured depends on the bandwidth of the transmitted signal and the ratio of signal energy to noise energy (SNR). In addition, measurement accuracy might be limited by such practical restrictions as the accuracy of the frequency-measuring device, nonlinearities in linear frequency sweep, errors caused by multiple reflections and transmitter leakage, the residual path length error caused by circuits and transmission lines and the frequency error due to the turn around regions of the frequency modulation.

If a general cycle counter, which measures the number of cycles or half cycles of the beat during the modulation period, is used as a frequency-measuring device then the total cycle count is a discrete number since the counter is unable to measure fractions of a cycle. The discreteness of the frequency measurement gives rise to an error called the fixed error, quantization error, or range accuracy [13]. The average number of cycles N of the beat frequency f_b in one period of the modulation cycle f_m is equal to f_b/f_m. Therefore (3) may be written as:

$$R = \frac{cN}{4\Delta f} \tag{4}$$

Since output of the frequency counter N is an integer, the range will be an integer multiple of $c/4\Delta f$ and will give rise to quantization error equal to:

$$\delta R = \frac{c}{4\Delta f} \tag{5}$$

In our ZCC, beat frequency is calculated by measuring the time interval between successive rising edges of the signal instead of counting the zero crossings during the modulation period, T_m. Therefore, range accuracy can be calculated using (3) as:

$$\delta R = \frac{c \cdot \delta f_b}{4\Delta f \cdot f_m} \tag{6}$$

The frequency is calculated from the counter content difference of the PIC16F877 for every rising edge hence, the beat frequency is calculated as:

$$f_b = \left(\frac{1}{N \cdot \Delta T}\right) \tag{7}$$

where N is the timer content and ΔT is the instruction cycle of PIC, i.e. time between consecutive timer increments. Hence, the frequency accuracy can be calculated for our ZCC as:

$$\delta f_b = \left(\frac{1}{(N+1)\cdot \Delta T} - \frac{1}{N \cdot \Delta T}\right) = \frac{1}{(N+1)\cdot N \cdot \Delta T} = \frac{f_b}{N+1} \tag{8}$$

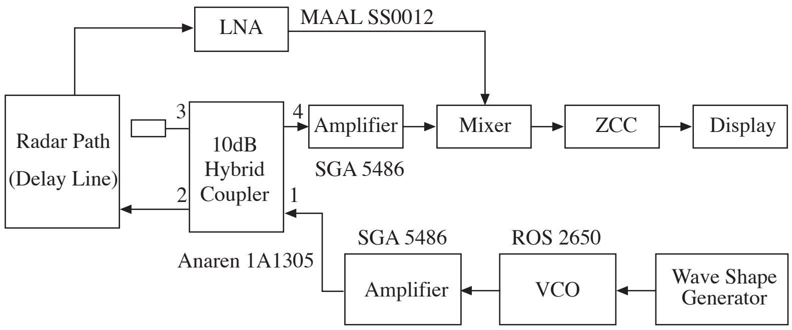
Using (6) in (7), the range accuracy is calculated as:

$$\delta R = \frac{c \cdot f_b}{4\Delta f \cdot f_m \cdot (N+1)} \tag{9}$$

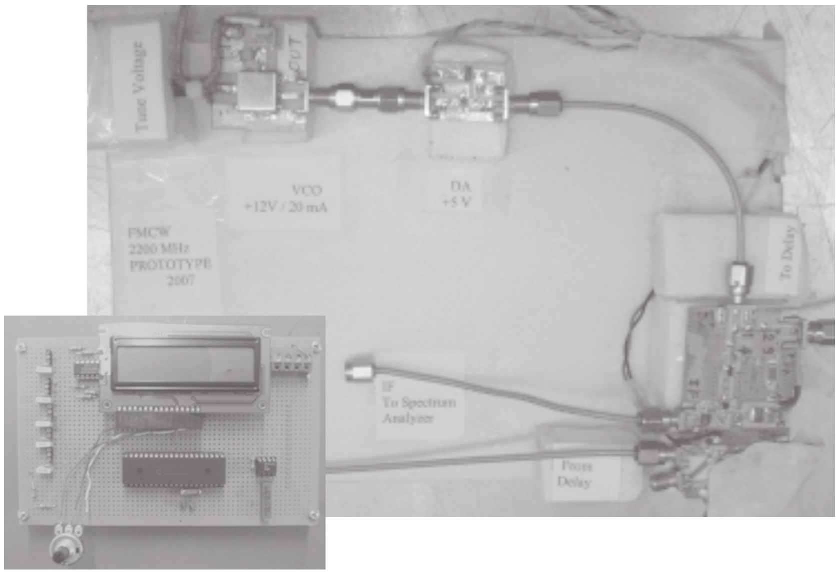
Comparing (9) with (5), it is seen that the range accuracy is $\frac{f_b}{f_m \cdot (N+1)}$ times better for our ZCC than a general cycle counter. The instruction cycle ΔT is 200 ns. Considering the proper values for f_b and f_m in the experimental setup it is seen that our ZCC has a range accuracy at least 6 times better than a general cycle counter and can further be increased by proper adjustment of the parameters according to the application specifications.

4. Experimental Evaluation

The block diagram and photograph of the prototype 2200 MHz FMCW system used in the experiments for ZCC measurement evaluation is given in Figure 5.



(a)



(b)

Figure 5. (a) Block diagram and (b) photograph of the prototype FMCW radar system.

In the prototype 10 dB hybrid coupler is used instead of the circulator used in the general FMCW radar case. The 10 dB hybrid coupler usage for this structure is proposed in [14]. The transmitting signal is given to port 1 of the coupler. Port 3 is terminated. The signal flowing through port 4 is used as the transmitted signal for mixer and delayed version of the signal coming from the delay line is used as the echo signal. Delay lines of different lengths are used to simulate the radar path to eliminate the effect of the multiple reflections and the antenna mismatch. The beat frequency is determined by feeding the IF signal from the mixer to the ZCC.

The determined beat frequency is displayed on the display unit and range is directly calculated from the beat frequency. Setup is arranged such that both the spectrum analyzer and the oscilloscope can be fed with the IF signal to be able to discuss the ZCC performance according to the spectrum of the IF signal and the time domain signal.

The characteristics of the IF signal are examined for various Δf, the frequency deviation, and f_m, the modulation frequency values. To be able to observe the effects of each parameter, measurements are done for four different parameter sets in which one parameter is kept constant while the others change. For the first two sets 76.07 ns delay line is used as the radar path and for the last two sets 69.02 ns delay line is used. For each set, consecutive readings from LCD are observed and for a number of readings minimum and maximum values are recorded. From these beat frequency readings of zero crossing counter the measured range is calculated and compared with the actual range. For the performance comparison of our ZCC, the δR improvement with respect to general cycle counters and the FFT resolution is given for each measurement data.

Table. The measurement results

	76.07 ns delay (11.41 m)				69.02 ns delay (10.35 m)	
	Set 1.a	Set 1.b	Set 2.a	Set 2.b	Set 3	Set 4
Δf(MHz)	105.8	105.8	92.3	92.3	88.8	132.3
f_m (kHz)	3	2	2	2.53	2.65	2
f_b (kHz)	47.8	31.7	27.8	34.9	31.7	36.3
Measurement errors (m)	-0.11 + 0.10	-0.17 + 0.14	-0.11 + 0.13	-0.20 + 0.01	-0.16 + 0.04	-0.16 + 0.17
δR Improvement w.r.t. a general cycle counter	6.6	10.0	13.0	10.5	13.3	7.6
Resolution for FFT (m)	1.42	1.42	1.62	1.62	1.70	1.14

Evaluating the measurement results, it can be deduced that ZCC is a good and low cost solution for short-range FMCW range detectors. The ZCC is a cost effective solution due to the simplicity of circuitry needed to implement. In addition, as seen in Table, the proposed ZCC is better than the common cycle counters for range accuracy.

In the measurements, ZCC displayed the averaged readings; the sequential readings are close to each other however, there are some erroneous readings in sequential set of readings. To improve the ZCC performance further, besides the averaging of the readings the order statistics can be used to eliminate the erroneous readings. Ordering a set of readings and using the median of these readings as the measured frequency may improve the performance. From the observations during the measurement, it is seen that such a process would improve ZCC reading stability and consequently the range measurement performance.

5. Conclusion

The ZCC implementation shows appreciably good performance during the experimental measurement. It is very simple and more suitable for short range applications as compared to the other signal processing methods for longer range systems using FFT. There exist some other methods that can achieve better range measurement accuracies than the ZCC in the expense of higher computational load, consequently higher complexity, and cost. Nevertheless, the proposed ZCC has very simple circuitry with commercially available low cost components. It is also better in range accuracy than commons cycle counters used in for FMCW range detectors. The main disadvantage of ZCC detector is inability to detect multiple targets. Therefore, it is applicable for short range detection applications such as level gauging systems, radio altimeter, and collision avoidance.

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