International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 4 Issue 09, September-2015

Design and FPGA Implementation of a Modified Radio Altimeter Signal Processor

A. Nasser, Fathy M. Ahmed, K. H. Moustafa, Ayman Elshabrawy
Military Technical Collage
Cairo, Egypt

***Abstract*—Radio altimeter for artillery projectile proximity fuzes is one of the critical applications that are constrained by the requirements of cost, size, weight, power, and real time operation. Traditional radio altimeter signal processor used in proximity fuzes for artillery projectiles has the disadvantage of degraded detection probability in bad weather condition, existence of two or more targets, and when the target echo frequency is off-bin while using the standard Periodogram frequency estimation technique. This degradation causes an error in altitude measurements which affects the proximity fuzes decision to detonate the explosive charge. In this paper, FPGA based embedded system is used to design and implement a modified radio altimeter signal processor for artillery projectiles proximity fuzes. The proposed radio altimeter signal processor overcomes the disadvantages of the traditional one by applying Welch method for frequency estimation, instead of the standard Periodogram, in conjunction with an optimum Constant False Alarm Rate (CFAR) scheme. The superiority of the proposed processor over the traditional one is validated through the Receiver Operating Characteristic (ROC).**

Keywords—Radio Altimeter;Welch;FFT;FPGA;LFMCW;

I. INTRODUCTION

Radio altimeter is one of the early applications of FMCW radar that measures the altitude above the terrain and being used for airplanes or spacecrafts. It provides the distance between the plane and the ground. This type is used especially for landing in low visibility conditions. It is also very critical in low altitude flies and used as terrain avoidance system.

Radio altimeters are used also as the proximity sensor in proximity fuzes used in artillery projectiles. They have the advantages of having simple solid-state transmitters, they are resistant to Electronic Countermeasure (ECM), they have good range resolution, they have good range accuracy, they have quick updating of measurement, they function well in many types of weather and atmospheric conditions, they have better electrical and radiation safety, they can penetrate variety of materials, they are better at detecting tangential motion than Doppler based systems, and the simplicity of signal processing [1, 2, 3].

The basic radio altimeter, shown in Fig. 1, consists of three major parts: transmitter, receiver and the antennas for transmitting and receiving the radio waves. The transmitter consists of a modulator, voltage controlled oscillator (VCO), and power amplifier (PA). The receiver consists of Low Noise Amplifier (LNA), mixer and Intermediate Frequency (IF) amplifier. The output of the receiver is fed to the signal processing part which is the core of this paper [1, 4, 5]. The basic function of a signal processor is to extract the range information from the output of the IF amplifier. When the radio altimeter is used as the proximity sensor for proximity fuzes, the signal processing circuit can be quite complex since it must overcome different kinds of noise, interference and jamming environments [2].

The signal processor extracts the range information by estimating the frequency of the IF signal from its time domain using a time to frequency estimation technique. Then, it uses Constant False Alarm Rate (CFAR) processor to achieve automatic detection.

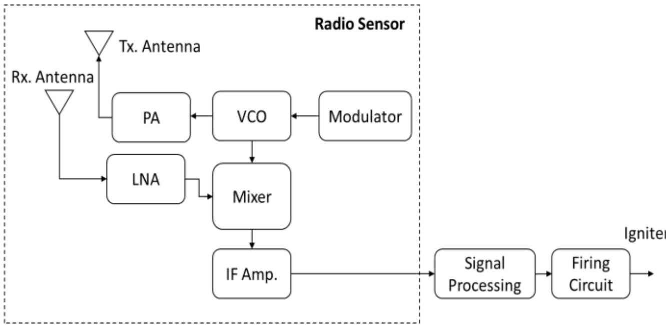


Fig. 1 Basic radio altimeter block diagram

The Traditional Radio Altimeter Signal Processor (TRASP) used in proximity fuzes for artillery projectiles has the disadvantage of degraded detection probability in bad weather condition (clutters), existence of two or more targets, and when the target echo frequency is off-bin while using the standard Periodogram in signal processing. According to this disadvantage, the benefits of using proximity fuzes may be lost. In this paper, a Proposed Radio Altimeter Signal Processor (PRASP) is introduced to overcome this problem and increase the detection probability of the TRASP in all cases. Also, Design and Implementation of a modified Radio Altimeter Signal Processor are introduced using FPGA based embedded system.

After the introduction, the rest of this paper is organized as follows; section II introduces the Traditional Radio Altimeter Signal Processor (TRASP). Section III discusses the possible enhancements in the TRASP. Section IV introduces the Proposed Radio Altimeter Signal Processor (PRASP). Implementation of the PRASP compared with that of the TRASP is introduced in section V. Finally, conclusion comes in section VI.

II. TRADITIONAL RADIO ALTIMETER SIGNAL PROCESSOR

The block diagram of the TRASP for the LFMCW radio proximity fuzes of Fig. 1 is shown in Fig. 2. It consists of three major parts: standard Periodogram technique as a time to frequency estimation technique, CFAR processor to achieve automatic detection, and the ignition circuit which activates the firing circuit at the desired altitude [1].

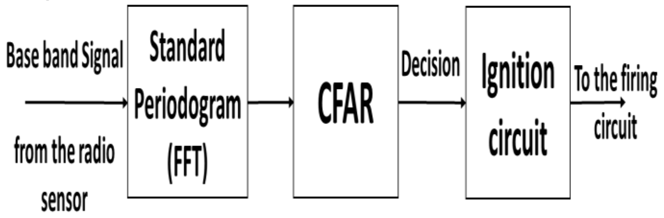


Fig. 2 Traditional radio altimeter signal processor

It is necessary to study the performance of the TRASP in different scenarios in order to improve its performance. Four scenarios are assumed. The first scenario is in-bin frequency target (range cell = 20), the second scenario is off-bin frequency target (range cell = 20.5), the third scenario is off-bin frequency target (range cell = 20.5) with existance of another target at (range cell = 14), and the forth scenario is off-bin frequency target (range cell = 20.5) with existance of another target at (range cell = 14) with addition of Clutter to Noise Ratio (CNR = 10dB).The Receiver Operating Characteristics (ROC) is a performance measure of the TRASP. A MATLAB program is written to calculate the ROC. The assumed parameters are:

Sweep time = 1ms, maximum range (R_{max} = 1 km).

Beat frequency (f_{bmax} = 1MHz).

Sampling frequency (f_s = 2MHz).

N(number of FFT points)=2048.

Doppler frequency (f_D = 5 kHz),Number of iterations = 10000.

Probability of false alarm ($P_{fa} = 10^{-5}$).

Fig. 3 shows the ROC of the TRASP in case of in-bin frequency target. The detection probability of the TRASP decreased in case of off-bin frequency target as shown in Fig. 4. For example at (SNR= -10 dB).the detection probability of the TRASP is (100%) in case of in-bin frequency target, while it is (75%) in case of off-bin frequency target.

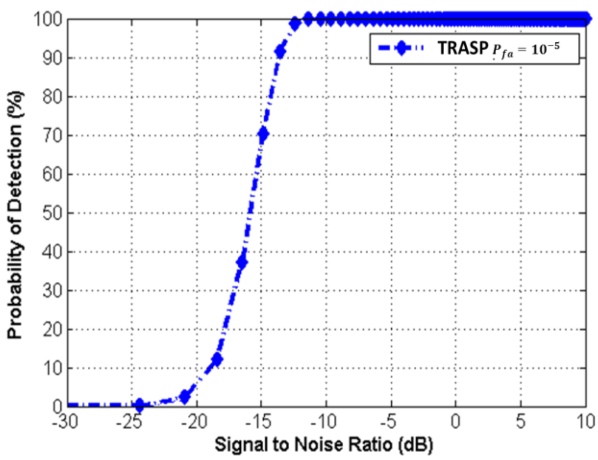


Fig. 3 ROC of the TRASP in case of in-bin frequency target

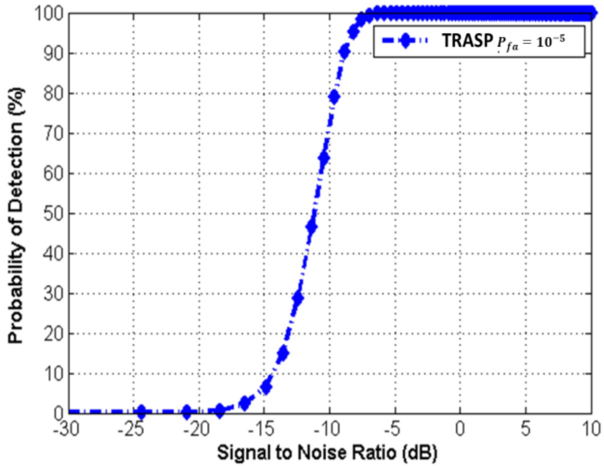


Fig. 4 ROC of the TRASP in case of off-bin frequency target

Fig. 5 and Fig. 6 show the ROC of the TRASP in case of off-bin frequency target with existance of another target and in case of off-bin frequency target with existance of another target with addition of (CNR = 10dB) respectively. These figures show the problem of the TRASP that there is no detection of the target in both cases.

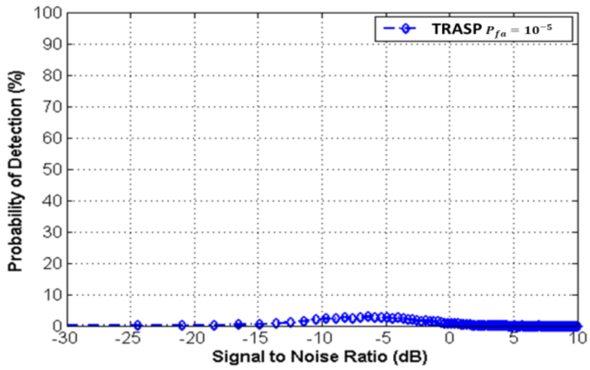


Fig. 5 ROC of the TRASP in case of off-bin frequency target with existance of another target

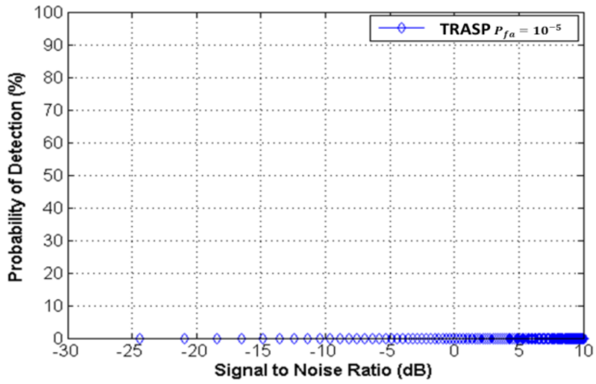


Fig. 6 ROC of the TRASP in case of off-bin frequency target with existance of another target and CNR=10dB

It is necessary to study the way to overcome the detection problems of the TRASP. So, possible enhancements of each part of the TRASP parts are studied in the following section.

III. Possible Enhancements in The TRASP

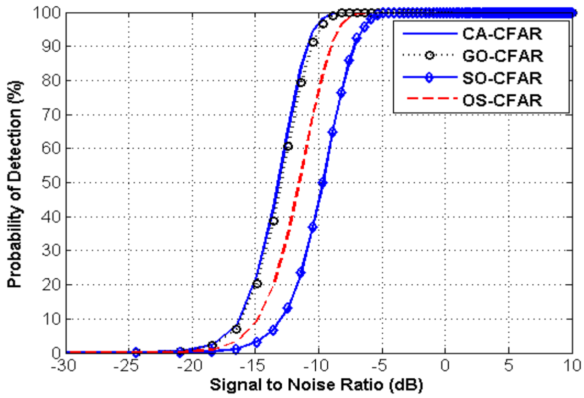
As the TRASP consists of three parts, possible enhancement in each part is important to increase the detection probability of the TRASP. These points are covered in the following subsections.

A. *Possible enhancements in CFAR module*

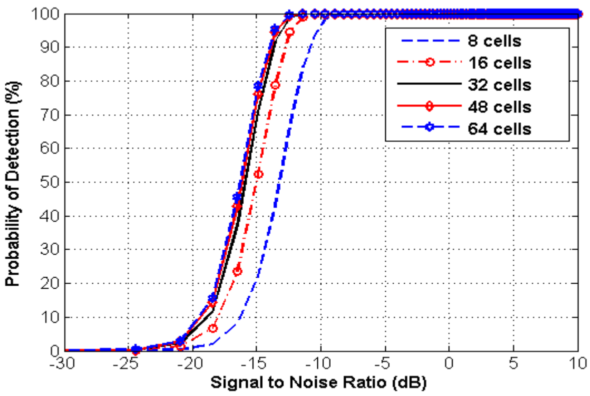
CFAR processor has several types, Cell Average (CA-CFAR), Greatest of (GO-CFAR), Smallest of (SO-CFAR) and Order Statistics (OS-CFAR). CA-CFAR is the optimum CFAR type to be used with homogenous background. While GO-CFAR is very useful in clutter edges but it has a loss in detection in homogenous background, SO-CFAR is very useful in multiple targets situations and OS-CFAR is very useful in clutter transitions and multiple targets situation but it takes more time for calculations [6].

In the present work, the maximum range is 1km. For this range the background is assumed to be homogenous. So, CA-CFAR is the optimum CFAR type to be used [6]. Also according to [6], the optimum window length for the CA-CFAR is 32 cells, 16 cells in each reference window.

To validate the previous discussion, the Receiver Operating Characteristics (ROC) of the TRASP with different types of CFAR processors with the same window length (32 cells) is shown in Fig. 7a, and ROC of the TRASP with CA-CFAR processor with different window lengths is shown in Fig. 7b.



(a)



(b)

Fig. 7 ROC of the TRASP
(a) with different types of CFAR processors
(b) with CA-CFAR processor with different window length

As shown in Fig. 7, CA-CFAR processor (with 32 cells window length), 16 cells in each reference window, is the optimum choice to be used.

B. *Possible enhancements in time to frequency estimation technique module*

There are several time to frequency estimation variants that can be used instead of the standard Periodogram such as Bartlett, Welch, complex Bartlett, and complex welch [7]. Other time frequency estimation techniques such as Wigner Ville Distribution (WVD) [8], and Summed Wigner Ville distribution (SWVD) [9, 10] may be used.

Before comparing the performance of the LFMCW radio altimeter signal processor using different frequency estimation techniques, these techniques should be described mathematically. For the discrete base band signal x(n):

$$x(n) = A * \cos(2\pi f n) \qquad (1)$$

The standard Periodogram is calculated by calculating the FFT of the total (2048) received discrete signal x(n). The standard Periodogram is given by [7]:

$$X(f_k) = \frac{1}{N}\left|\sum_{n=0}^{N-1} x(n) e^{-j2\pi n f_k}\right|^2 \qquad (2)$$

Where, k = 0, 1... N-1 and $f_k = k/N$.

The Bartlett method divides the discrete base band signal x(n) into a group of non-overlapped equal (K=2) segments. The Bartlett computes the Periodogram of each (1024) segment and then averaging over the K segments, this method increases the probability of target detection but on the other side, the range resolution decreases by (K). This degradation in range resolution doesn't affect the processor's function. The Bartlett method is given by [7]:

$$X_b(m) = \frac{1}{N}\sum_{i=0}^{K-1}\left|\sum_{n=0}^{M-1} x_i(n) e^{-\frac{j2\pi nm}{M}}\right|^2 \qquad (3)$$

Where, M is the number of non-overlapped segments.

The complex Bartlett method is derived from the Bartlett method. The main difference is that instead of computing the Periodogram of each segment and then averaging over the K segments; the spectrum components of all segments are added first. Then magnitude, squaring, and division over N are preformed [7]. Also, the range resolution decreases by (K). This degradation in range resolution doesn't affect the processor's function. The complex Bartlett is given by [7]:

$$X_{cb}(m) = \frac{1}{N}\left|\sum_{i=0}^{K-1}\sum_{n=0}^{M-1} x_i(n) e^{-\frac{j2\pi nm}{M}}\right|^2 \qquad (4)$$

Welch and complex welch methods are as the same as Bartlett and complex Bartlett methods except that they overlaps the segments by 50% between them, the optimum overlap is 50% between the segments to decrease the system hardware complexity. But the target detection probability in these methods increases more than that of Bartlett or complex Bartlett methods because the number of segments increases which causes the average noise to be decreased. Also, on the other hand the range resolution decreases. This degradation in range resolution doesn't affect the processor's function.

In WVD, time-varying signals whose spectral characteristics vary with time, such as radar signals, are analyzed perfectly with the (WVD) which is a time- frequency signal representation. The discrete-time version of WVD of the (1024) discrete base band signal x(n) is given by [8]:

$$WVD\,(n, 2f) = \sum_{m=-\infty}^{\infty} kernel * e^{-j2\pi f m \Delta t} \qquad (5)$$

Where, Δt is the sampling interval, n, m are integers and the kernel is $x\left\{(n+\frac{m}{2})\Delta t\right\} x^{*}\left\{(n-\frac{m}{2})\Delta t\right\}$.

In SWVD method, WVD is used as a 1D operation to calculate only the frequency of (1024) signal. Cross-products are calculated for all time index n = 0 to N-1, then the summation is applied over time on complex cross-products to generate summed kernel, instead of calculating the kernel only at time n = 0 as in WVD method. The FFT of the summed kernel gives the frequency spectrum of the signal. This method also decreases the range resolution by (K). This degradation in range resolution doesn't affect the processor's function. The SWVD proposed in [9, 10] is given by:

$$SWVD\,(m) = \frac{1}{N}\left|\sum_{k=0}^{N-1} SR(k)\, e^{-\frac{j2\pi k m}{N}}\right| \qquad (6)$$

Where, m = 0…N-1.

$$SR(k) = \begin{cases} \sum_{n=k}^{N-k-1} x(n+k)x^{*}(n-k), & k = 0, \dots, \frac{N}{2}-1 \\ 0 & , k = \frac{N}{2}\ , N \text{ is even} \\ SR^{*}(N-k-1), & k = \frac{N}{2}+1, \dots, N-1 \end{cases} \qquad (7)$$

Where, m is the normalized frequency index and n is discrete time index. SR(k) is the summed cross products of discrete signal x (n).

Fig. 8, Fig. 9, Fig. 10, and Fig. 11 show the ROC for the radio frequency altimeter proximity fuze signal processor using different time to frequency estimation techniques with CA-CFAR processor with (32 cells window length) in the assumed four different scenarios. Welch method has higher detection probability than that of the other time to frequency estimation techniques. Also, Welch method overcomes the problems in the standard Periodogram technique. So, Welch method is the optimum time to frequency estimation technique to be used in a PRASP for the LFMCW proximity fuzes.

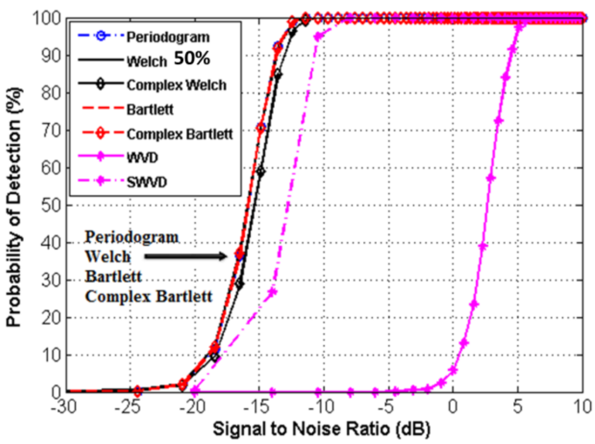


Fig. 8 ROC for the radio frequency altimeter proximity fuze signal processor using different time to frequency estimation techniques with CA-CFAR in case of in-bin frequency target

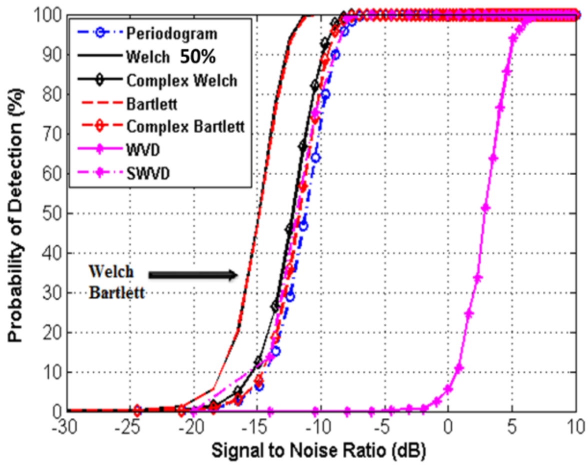


Fig. 9 ROC for the radio frequency altimeter proximity fuze signal processor using different time to frequency estimation techniques with CA-CFAR in case of off-bin frequency target

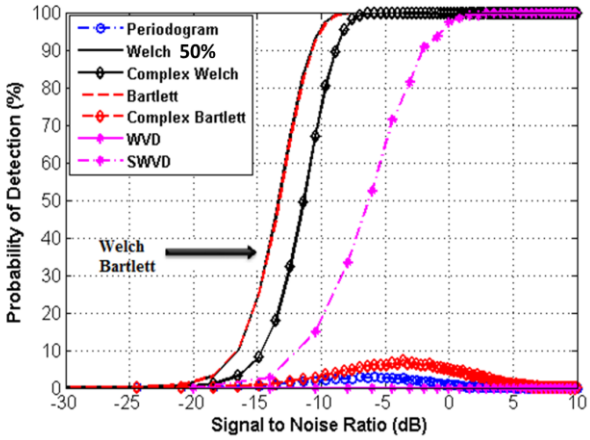


Fig. 10 ROC for the radio frequency altimeter proximity fuze signal processor using different time to frequency estimation techniques with CA-CFAR in case of off-bin target with existance of another target

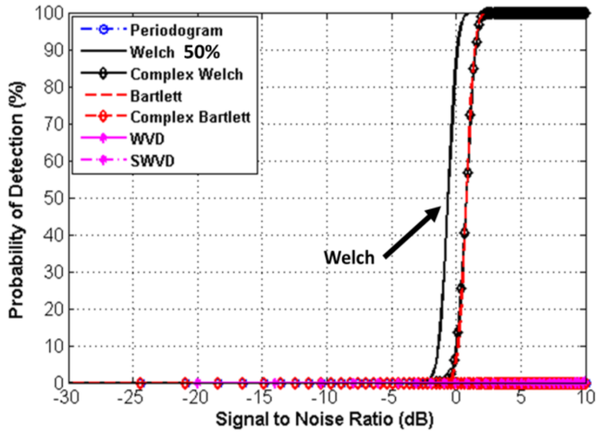


Fig. 11 ROC for the radio frequency altimeter proximity fuze signal processor using different time to frequency estimation techniques with CA-CFAR in case of off-bin target with existance of another target and CNR=10dB

IV. A Proposed Radio Altimiter Signal Processor

The block diagram of a PRASP for the LFMCW proximity fuzes of Fig. 1 is shown in Fig. 12. The PRASP consists of three major parts: Welch method as a time to frequency estimation technique, CA-CFAR processor with (32 cells window length) to achieve automatic detection, and the ignition circuit which activates the firing circuit at the desired altitude.

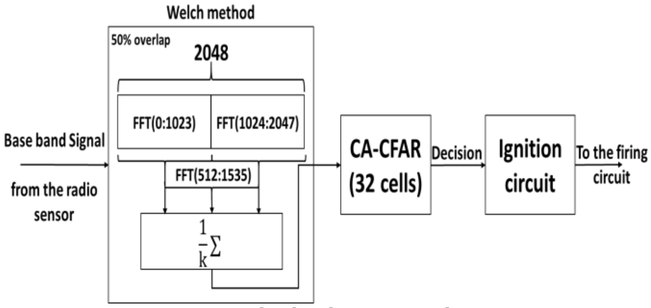


Fig. 12 Proposed radio altimeter signal processor

Fig. 13 and Fig. 14 show the ROC of a comparison between the detection probability of the TRASP with the PRASP in case of in-bin frequency target and off-bin frequency target respectively. In case of in-bin frequency target, both processors have the same detection probability, but in case of off-bin frequency target, the detection probability of the PRASP is higher than that of the TRASP. For example, at (SNR=10 dB) the detection probability of the PRASP is (100%) while the detection probability of the TRASP is (75%).

Fig. 15 and Fig. 16 show the ROC of a comparison between the TRASP with the PRASP in case off off-bin frequency target with existance of another target and in case of off-bin frequency target with existance of another target with addition of CNR = 10dB. Both figures show the superiority of the PRASP over the TRASP.

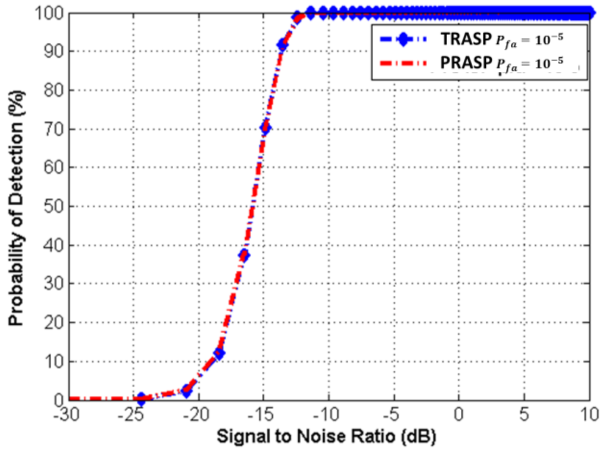


Fig. 13 ROC of the TRASP compared with the PRASP in case of in-bin frequency target

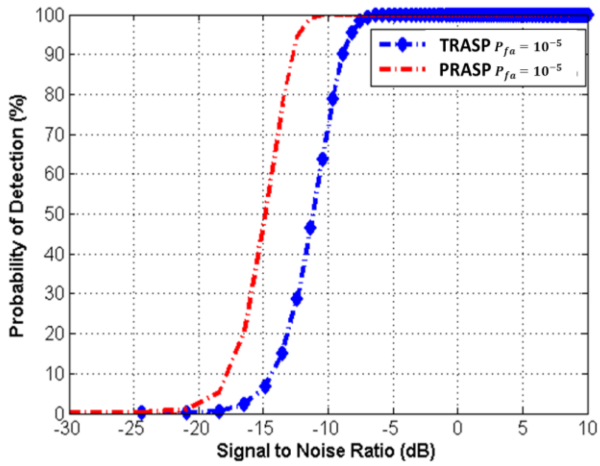


Fig. 14 ROC of the TRASP compared with the PRASP in case of in-bin frequency target

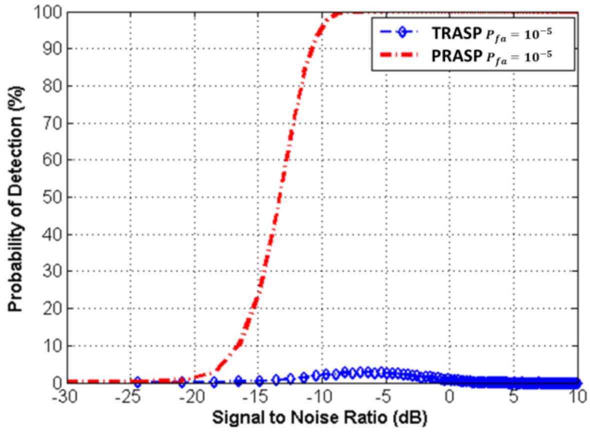


Fig. 15 ROC of the TRASP compared with the PRASP in case of off-bin frequency target with existance of another target

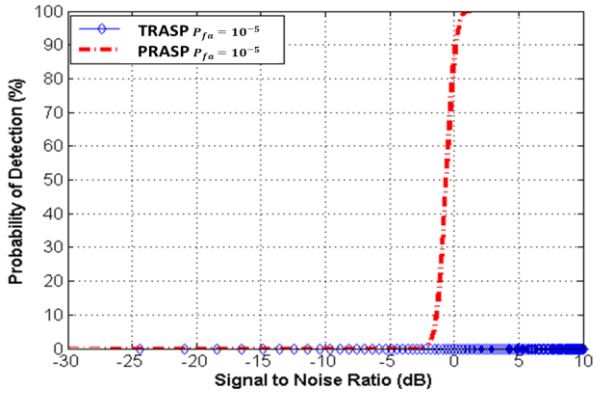


Fig. 16 ROC of the TRASP compared with the PRASP in case of off-bin frequency target with existance of another target and CNR=10dB

V. IMPLEMENTATION

In this section, design and implementation for the Proposed Radio Altimeter Signal Processor (PRASP) are introduced using FPGA based embedded systems [11]. Different companies produce different development kits to be used for embedded system prototype designing, downloading, and testing. In the present work, "Spartan-3A DSP 1800A board" is used [12]. Different companies produce different software packages for design and simulation using FPGA. In the present paper, Xilinx ISE release 13.2, Altera Modelsim 6.5, and Xilinx Chip scope are used for design, simulation and experimental testing.

The simplified block diagram of the hardware implementation of the proposed radio altimeter signal processor (PRASP) is shown in Fig. 17.

A. Experimental performance evaluation of the PRASP

The radar signal simulator is used to test the PRASP for different target scenarios. First one moving target is assumed to be at ranges (23m, 22m, 21m, and 20m) from the radio sensor. Second scenario is two moving targets, separated by 6m, are assumed to be at ranges (23.5m, 22.5m, 21.5m, and 20.5m) for one target (off-bin frequency), the desired altitude, and (17m, 16m, 15m, and 14m) for the other target.

The following subsections present different Modelsim timing simulation of the PRASP design at different target scenarios as well as the experimental measurements using Chipscope.

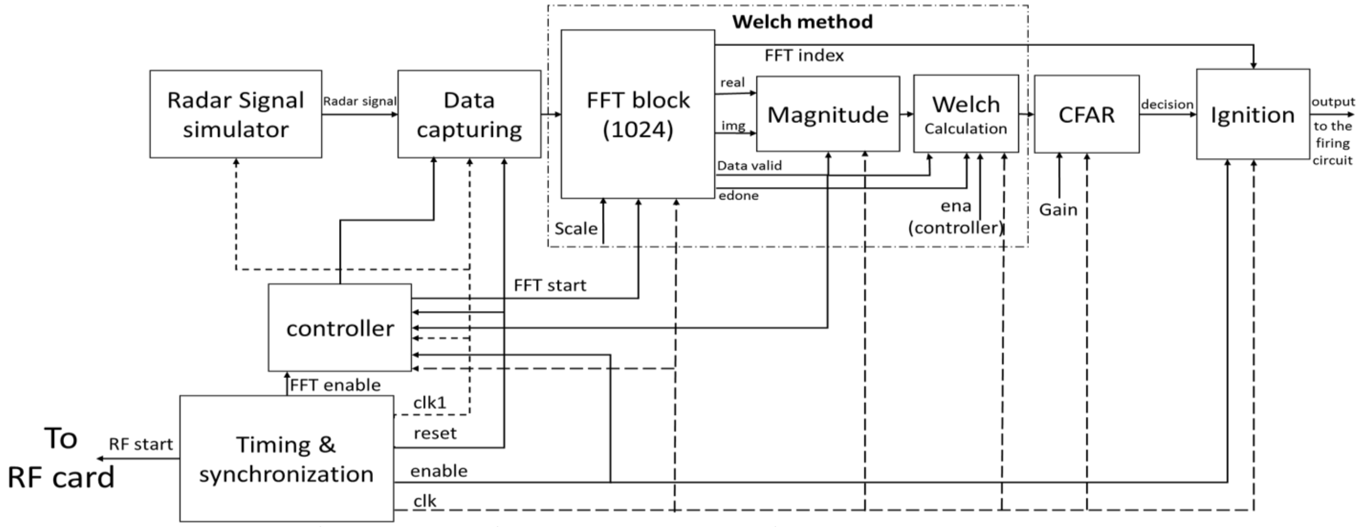


Fig. 17 Simplified block diagram of the hardware implementation of the proposed radio altimeter signal processor

1) Modelsim timing simulation results

Fig. 18 and Fig. 19 show the result of the Modelsim timing simulation for different target scenarios for the assumed radar parameters. In the first case of one moving target, the target range and the detonation signal decision are taken accurately. Also in the second case of two moving targets, both targets are detected accurately and the detonation signal decision is taken in the desired position.

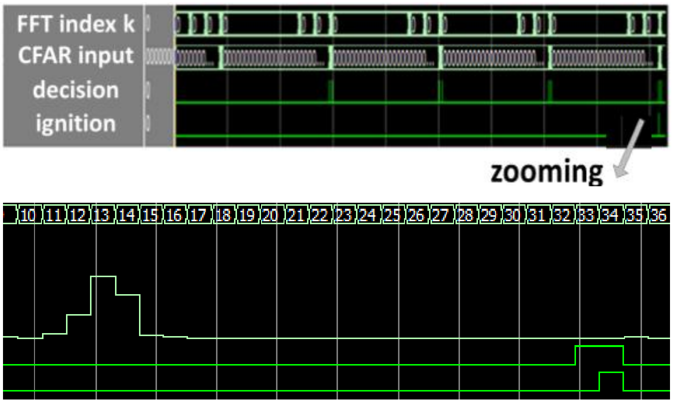


Fig. 18 Detailed Modelsim timing simulation in case of one moving target

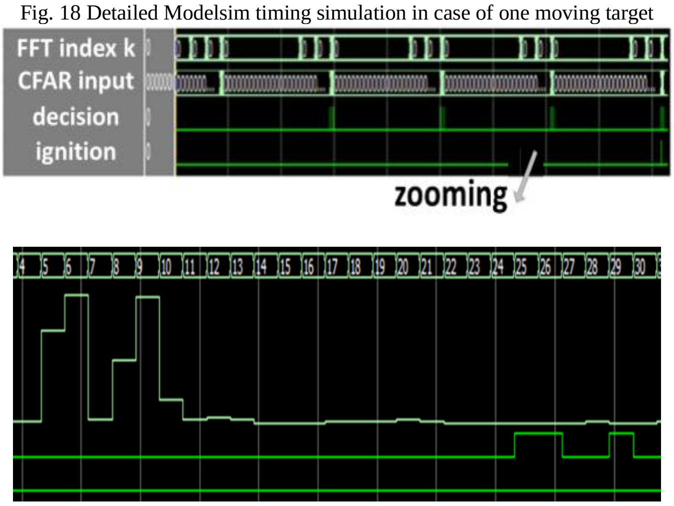


Fig. 19 Detailed Modelsim timing simulation in case of two moving targets

2) Experimental results using Chipscope

Fig. 20 and Fig. 21 show the experimental results for the PRASP in case of one and two moving targets using Chipscope. These results agreed with the obtained simulation results.

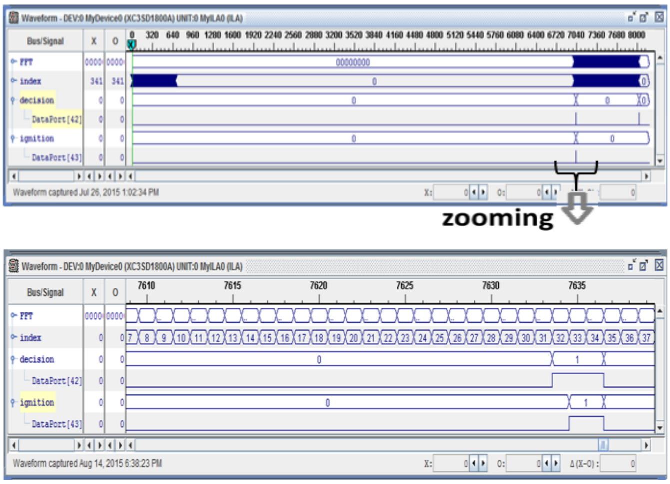


Fig. 20 Chipscope results in case of one moving target at range

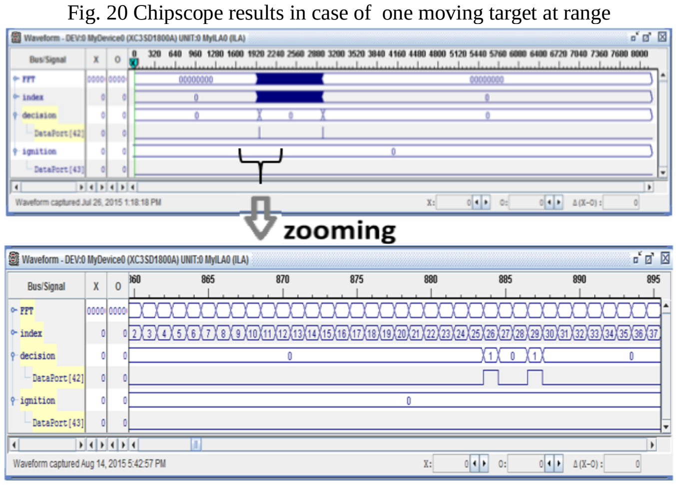


Fig. 21 Chipscope results in case of two moving targets

B. *Hardware complexity and processing time evaluation*

Hardware complexity evaluation and processing time evaluation for the traditional and proposed radio altimeter signal processors are shown in Table I.

Hardware complexity is an important point to be taken into consideration when realizing any hardware system. For the traditional and proposed approaches considered using FPGAs, the comparison is in terms of the used resources of the FPGA device used in implementation. The processing time here means the time taken by the input signal to be processed and correctly appears at the output of the system.

Table I Hardware complexity evaluation and processing time evaluation for the TRASP and PRASP

Processor	Hardware complexity	Processing time
TRASP	12 %	311.28 µsec
PRASP	12 %	440.48 µsec

Hardware complexity of the PRASP is as the same as hardware complexity of the TRASP (12% of the used FPGA chip). The PRASP processing time (440.48 µsec) takes 129.2 µsec longer than the TRASP processing time (311.28 µsec). This small extra time corresponds to a distance of 12.92 cm of moving missile with 1000 m/s speed. This delay does not affect real time operation of the system and is tolerable regarding to the achieved improvements

VI. CONCLUSION

Design and implementation of a Proposed Radio Altimeter Signal Processor (PRASP) for artillery projectiles proximity fuzes using FPGA based embedded system have been achieved. The PRASP overcomes the problem of detection probability degradation of the Traditional Radio Altimeter Signal Processor (TRASP) in case of bad weather condition (clutters), existence of two or more targets, and when the target echo frequency is off-bin. These improvements have been achieved by replacing the standard Periodogram in the TRASP by Welch frequency estimation method with 50% overlap. This superiority has been validated based on ROC curves. On the other hand, the range resolution of the PRASP decreased by two (the range resolution of the TRASP = 1m and for the PRASP = 2m) but it doesn’t affect the processor operation. Hardware complexity of the PRASP is as the same as hardware complexity of the TRASP (12% of the used FPGA chip). The PRASP processing time (440.48 µsec) takes 129.2 µsec longer than the TRASP processing time (311.28 µsec). This small extra time corresponds to a distance of 12.92 cm of moving missile with 1000 m/s speed. This delay does not affect real time operation of the system and is tolerable regarding to the achieved improvements.

REFERENCES

[1] V. K. ARORA, Proximity Fuzes Theory And Techniques, First ed.: Defence Research & Development Organisation, new delhi, 2010.

[2] A. Nasser, F. M. Ahmed, K. H. Moustafa, and A. Elshabrawy, "Recent Advancements in Proximity Fuzes Technology", in International Journal of Engineering Research and Technology, Vol. 4, pp. 1233-1238, 2015.

[3] A. G. Stove, "Linear FMCW radar techniques", in IEE Proceedings F (Radar and Signal Processing), pp. 343-350, 1992.

[4] C. A. Balanis, Antenna theory: analysis and design: John Wiley & Sons, 2012.

[5] M. Skolnik, Introduction to Radar Systems,: McGraw-Hill, 1980.

[6] A. Moustafa, F. M. Ahmed, K. Moustafa, and Y. Halwagy, "A new CFAR processor based on guard cells information", IEEE Conference in Radar, pp. 0133-0137, 2012.

[7] F. M. Ahmed, K. A. Elbarbary, and A. R. H. Elbardawiny, "A New Approach for Moving Target Detection using Bartlett Method for Spectral Estimation", in Wireless and Optical Communications Proceedings, pp. 46-51, 2006.

[8] P. K. Kumar and K. Prabhu, "Simulation studies of moving-target detection: A new approach with Wigner-Ville distribution", IEE Proceedings in Radar, Sonar and Navigation, pp. 259-265, 1997.

[9] S. G. Qadir, Y. Fan, and F. M. Ahmed, "A Wigner Ville Distribution Based Method for Detection of Gaussian Contaminated Sinusoidal Signal in Frequency Domain", PIERS Proceedings, Marrakesh, MOROCCO, 2011.

[10] Ibrahim M. Ali, Fathy M. Ahmed, "Application of a Wigner Ville Distribution Based Method in Moving Target Detection", International Journal of Engineering and Advanced Technology (IJEAT), vol. 3, pp. 2249-8958, December 2013.

[11] R. Dubey, Introduction to embedded system design using field programmable gate arrays: Springer, 2009.

[12] http://www.xilinx.com/products/boards-and-kits/hw-sd1800a-dsp-sb-uni-g.html.