Random Delay Mitigation in Pulse Radar Implementation on Universal Software Radio Peripheral (USRP)

Alifia Fitri Utami[1], Iswandi[2], I Wayan Mustika[3]

***Abstract*— Software defined radio (SDR) has great potential to construct radar systems. The universal software radio peripheral (USRP) and GNU radio companion (GRC) are most popular hardware and software in the researches to design SDR for radar systems. Although some types of radar have been successfully developed by USRP, but it faces difficulties to construct it for pulse radar. One of probable reason is the random delay issue in the processing on USRP. This research aims to analyze the random time delay in the pulse radar system implementation by using USRP and GRC. The measurement shows the average time delay is 0.0625 ms with standard deviation of 0.053 ms. The higher variability of random delay caused difficulty on ranging process of pulsed radar with USRP. In addition, a mitigation technique to compensate the delay problem is done by transmitting 128 bits of Barker code and performing correlation between transmitted and received radar signals. Then problems with random time delay in this system implementation can be overcome by using direct reception from the transmitting antenna to the receiving antenna as a reference. The result shows the target is successfully detected but the second target suffers from 6.7% measurement error after the correction of time reference.**

***Keywords*— Pulse radar, SDR, USRP, GRC, time delay**

I. INTRODUCTION

In the recent years, the development of radar system on software-defined radio (SDR) has attracted attentions amongst researcher and academia. SDR has flexibility to perform as multipurpose radar, reuse hardware, and low production cost. Moreover, since most of hardware except in the RF sites is replaced by software, it is much easier on the signal processing development [1].

One of popular hardware for SDR implementation is universal software radio Peripheral (USRP) hardware from Ettus Research and its parent company, National Instrument [2]. Although USRP can be programmed by using various software, the GNU radio companion (GRC) is the most often used in published researches since it is open source and operated in easy graphical programming [3].

Many efforts have been established by researchers to construct USRP as software defined radar with various radar types. The most common one is frequency modulated continuous wave (FMCW) radar as done in [1],[4]-[6]. In general, the USRP has well performance under FMCW to detect target with limited distance due to the constraint on its output power. The other type of USRP based radar is OFDM radar [7], [8]. They have successfully developed the radar for short-range implementation such as in doorway detection [7] and radar on vehicle [8]. Other radar types has also developed on USRP that are not listed here, but they mostly the enhancement of continuous wave radar. This paper intention is on the development of pulse radar on USRP that has less attention by the researcher. Although there was an effort to simulate with GRC [9] but it could not be realized in the USRP. One reason is the limitation of USRP bandwidth to perform unmodulated pulse. In the other hand, as describe in [9] the communication between USRP and computer during its operation potentially produces the random delay time. Since the ranging calculation in pulse radar is merely based on the delay time between transmitted and received signals, the additional random delay causes difficulty the ranging process.

This paper empirically analyses time delay issues in the implementation of pulse radar on USRP by using GRC. In addition, the mitigation technique to recognize the delay time has also established in experiment by using 128 bits of Barker code as done also in [9].

II. RADAR PLATFORM

This sub-section describes the radar platform in the simulation and also experiments.

A. Pulse Radar

Pulse radar transmits modulated pulse/pulse sequence and receives the reflection from radar target. Distance from radar detected object (R) was obtained from time delay between the transmitted and received pulses (Δt), as in (1) with $c = 3.10^8$ m/s.

$$R = \frac{\Delta t \cdot c}{2} \tag{1}$$

Almost all pulse radar functions are time-dependent. Thus, synchronization between transmitter and receiver on the radar system is mandatory to measure the target distance.

A type of pulse radar that has high detection resolution is pulse compression radar. This radar type divides pulse sequence along T into N sub-pulse and each of which has a width of τ [10]. Radar distance resolution is shown by (2), with $c = 3.10^8$ m/s and bandwidth $B = \frac{1}{\tau}$.

$$R_{res} = \frac{c}{2B} \tag{2}$$

[1] *Department of Electrical and Information Engineering, Faculty of Engineering, Universitas Gadjah Mada, Jln. Grafika 2, Kampus UGM Yogyakarta 55281 INDONESIA (telp: 0274-552305; fax: 0274-552305; email: alifia.fitri.u@gmail.com)*

[2,3] *Lecturer, Department of Electrical and Information Engineering, Faculty of Engineering, Universitas Gadjah Mada, Jln. Grafika 2, Kampus UGM Yogyakarta 55281 INDONESIA (telp: 0274-552305; fax: 0274-552305; email: iswandi@ugm.ac.id, wmustika@ugm.ac.id*

TABLE I
BARKER CODE [11]

Code Length	Code Element	Side lobe Level (dB)
2	+ - + +	-6.0
3	+ + -	-9.5
4	+ + - + + + + -	-12
5	+ + + - +	-14.0
7	+ + + - - + -	-16.9
11	+ + + - - - + - - + -	-20.8
13	+ + + + + - - + + - + - +	-22.3

TABLE II
USRP N210 SPECIFICATIONS

Parameters	Values	Units
ADC Sample Rate	100	MS / s
ADC Resolution	14	Bits
DAC sample rate	400	MS / s
DAC Resolution	14	Bits
Host sample rate (8 bits/16 Bits)	50/25	MS / s
FPGA	Spartan 3A-DSp3400	-
Interface	Gigabit Ethernet	-

B. Barker Code

Barker code is suitable for radar applications because it can reach the lowest side lobe value on the correlation results among other codes [11]. A longer generated Barker code leads to a lower side lobe value compared to the main lobe. This is certainly better when it is used for radar applications. Table I shows the Barker codes types and side lobe reduction values in each code length.

C. Universal Software Radio Peripheral (USRP)

In this research, USRP performs several functions, including converting the RF frequency into an IF signal or the reverse process, converting analogue to digital and digital to analogue, and communicating with other devices/computers. In USRP, signal processing is administered by motherboard and daughterboard. The motherboard consists of integrated components such as ADC/DAC and FPGA used for computational purposes in data processing. Daughterboard is used as an interface for (RF) radio communication. Each USRP type has its own specifications that are tailored to the user needs and the functions to be performed. The specifications of used USRP N210 are shown in Table II.

D. GNU Radio Companion (GRC)

GRC is used in this research because it is free software and can provide various signal processing blocks for SDR implementation [3]. The main programming method is by using graphical flow-graphs based on provided block, but it can also uses C ++ programming language to modify the block content and Python to connect between blocks.

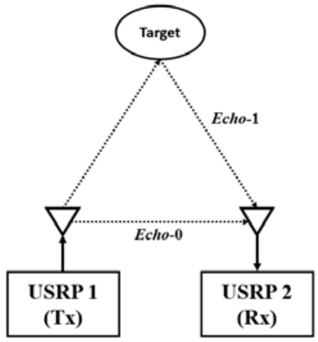

Fig. 1 Measurement setup.

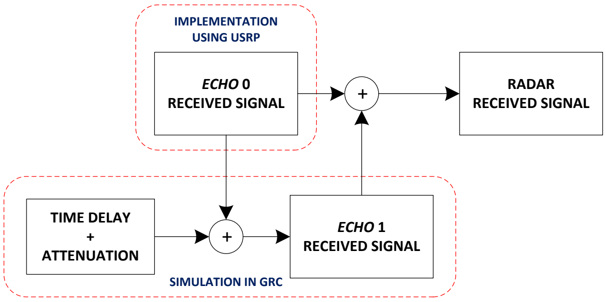

Fig. 2 Formation or radar's received signal signals at GRC.

III. METHODOLOGY

A. Random Time Delay Mitigation Design

In the system implementation using USRP and GRC, there is a random time delay due to processing time required by communication protocol to exchange information between computer running GRC and USRP. That issue can be anticipated by using direct reception from Tx to Rx as in [9].

In this paper, the used radar type is bistatic pulse compression radar. Therefore, receiver's USRP can directly receive transmission wave from USRP transmitter (without using any reflectors). The direct received wave is used as a reference to anticipate random time delay issues in pulse radar implementation using USRP. The test scheme is shown in Fig. 1.

Echo-0 is a direct received signal from transmitter to the receiver, while *echo*-1 is reflected signal from radar target. This implementation did not use real target due to the limited tools. GRC software in the computer was only able to compute with rate of 1 Msps, which is equivalent to detection distance resolution of 150 m. While the USRP antenna transmission power was only able to receive reflection from object with a distance of ± 5 m from the radar. Therefore, conducting a testing using reflection from the real object was not possible.

As a substitute, the object was modelled by delaying the radar received signal from *echo*-0 with Δt time delay representing r distance in the GRC program, and providing attenuation of x. Furthermore, data was processed in MATLAB software. The process to form radar-received signal is shown in Fig. 2.

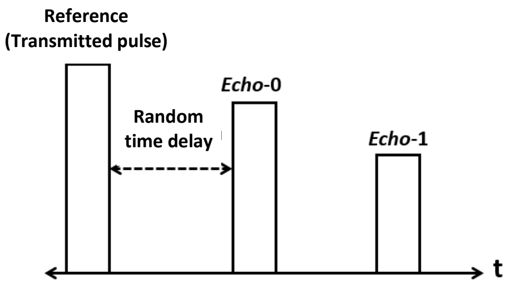

Fig. 3 Timing diagram of radar-received signal.

Timing diagram of the pulses received by the radar is shown in Fig. 3. Ideally, *echo-0* coincides with the transmitting pulse because the transmitter and receiver antennas have very close distances (± 15 cm). However, in reality there is a time delay which value is more than what is should be between the transmitted pulse with *echo*-0 due to time processing between USRP and computer. If no correction was made, then distance measurement to the target did not match the actual distance. To correct the ranging error, the *echo*-0 is used as reference.

B. Radar Transmitting Pulse Generation

Pulse radar transmitter sends a pulse sequence containing Barker code. The longest Barker code is 13, which has a side lobe reduction value of -22.3 dB. Whilst in practice, at least a side lobe reduction of -30 dB is required [12]. Therefore, Barker code value reduction needs to be increased by adding the length of Barker code series. It was elaborated by performing Kronecker product operation on the existing Barker code.

In this paper, Barker code series with length of 121 was composed by Kronecker product between 11 length identic Barker codes. In the receiver, a correlation process was carried out by FFT operation. Input from FFT operation was a length of 2^N sampled data sequence. To enable FFT operation on the transmitted data, a padding was added to the Barker Code series by inserting seven zeros (0) distributed in the beginning and the end of data sequence.

Transmitted radar series (128) = [0,0,0,B11 $\otimes$ B11,0,0,0,0] with

B11$\otimes$B11 = [+B11,+B11,+B11,-B11,-B11,-B11,+B11,-B11, -B11,+B11,-B11]; and

B11 = [+1,+1,+1,-1,-1,-1,+1,-1,-1,+1,-1].

C. Correlation Process on Radar Receiver

Cross-correlation is a similarity indicator between two function series of time delay. In the designed radar system, distance between radar and target was measured by comparing the signal transmission and reception time, so that a correlation operation required to be performed in radar signals processing

The correlation results between $u(t)$ and $v(t)$ is shown by (3).

$$w(t) = \int_{-\infty}^{\infty} u(\tau)v(\tau + t)d\tau. \quad (3)$$

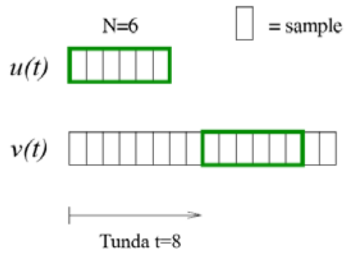

Fig. 4 Time delay in correlation process.

TABLE III
TEST PARAMETERS

System Parameters	Values
Working frequency	2.7 GHz
Sampling rate	1 MSps
Range resolution	150 m
Barker code length	128 bits
Tx-Rx antenna spacing	±15 cm

Value of t in (3) represents the time delay between two correlated signals. Time delay of the two signals is shown in Fig. 4.

In the frequency domain, correlation was calculated by multiplying a signal to the complex conjugate value of other signals. Correlation between two signals in the frequency sectors is indicated by (4).

$$W(s) = U^*(s)V(s) \quad (4)$$

IV. EXPERIMENT SCHEME

The program that has been created on GRC was implemented with USRP N210 hardware. Radar implementation used directional antenna so that the detection object direction could be determined. The antenna used in this test was the LP0965 log periodic antenna, a directional antenna with a working frequency of 850-6,500 MHz [13].

The test was carried out using two N210 USRP's, for transmitter and receiver respectively. The transmitting and receiving were programmed by using a computer which runs GRC program connected with USRP using Gigabit Ethernet cable. Test parameters are shown in Table III.

V. RESULTS AND ANALYSIS

A. Simulation on GRC

Simulation was run to determine the ideal condition that should occur in correlation process to calculate the distance between targets and radar. In addition, simulations were carried out to ensure that the utilized programs could function properly. The simulation results to calculate the distance of one and two targets are shown in Fig. 5.

If the time delay obtained from the correlation process was used to calculate the distance with (1), the obtained target distance was suitable with the distances entered in GRC simulation, which were 1,200 m and 2,400 m.

B. Time Delay Test at USRP

Ideally, the time difference between transmitted and received signal was close to zero because the antennas closely

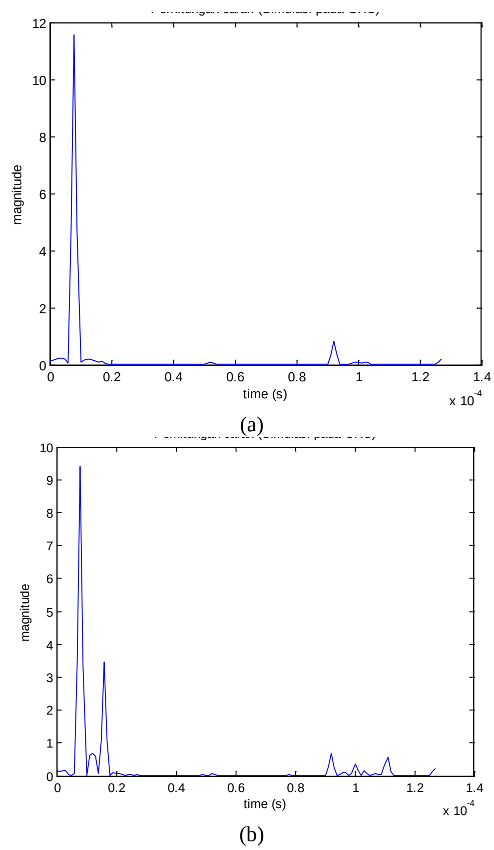

Fig. 5 Correlation results in the GRC simulation, (a) one target, (b) two targets.

spaced with only 15 cm spacing. The ideal time delay between transmitted and received signal is 10 µs, according to resolution of sampling rate at 1 Msps.

However, the measured time delay is much greater than the theoretical value. It is probably caused by data exchange process between USRP and a computer that requires time to channel information through Gigabit Ethernet. The time delay affected on the radar target distance calculation result. In this test, *echo*-0 (as shown in Fig. 1) was observed in 30 times observation. The acquired data are shown in Fig. 6.

From the test results, it can be seen that the time delay has random appearance. The delays are almost entirely varying in each trial. Unfortunately, the randomness of time delay seems not to have a specific pattern that can be used for threshold to separate it from transmission delay.

Average time delay between transmitted signal and *echo*-0 is 0.0625 ms, while the standard deviation is 0.053 ms. The large deviation shows the variability of delay is significantly high or data points are spread over a wide range. Therefore, it is impossible to use average value as a correction value in the designed radar system.

C. Random Time Delay Analysis of USRP Implementation

A method that can be used to overcome the random time delay problem in the implementation using USRP and GRC is by taking the direct transmission signal or *echo*-0 as a time reference in distance measurement. To validate the method, this research developed measurement with USRP for transmitter and receiver. Unfortunately, the designed radar has low range resolution so that it need long target distance to get separated direct transmission from transmitter and reflection echo from target. It should be noticed that USRP has only limited transmitter power so the maximum range is limited to assure the echo is higher than detection threshold. In this situation, the measurement campaign is conducted by some modification on the receiver site. The reflection echo is generated by GRC simulation and added to direct transmission signal from USRP reception.

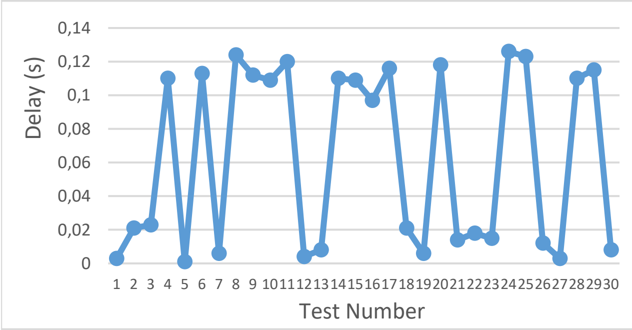

Fig. 6 *Echo*-0 time delay graph.

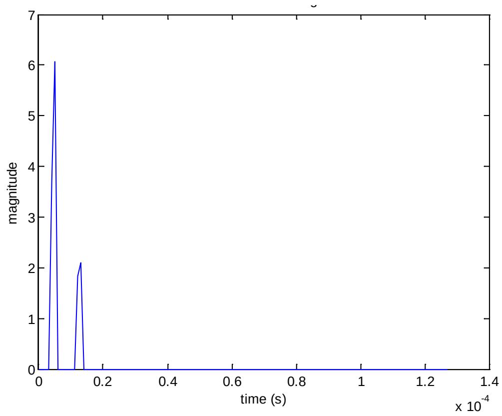

Fig. 7 Results of one target received signal correlation and transmitted signals.

In this test, the first echo signal *echo*-1 was formed from direct transmission signal with addition 8 µs delay, which represented a target distance of 1,200 m. Correlation results from radar received and transmitted signals are shown in Fig. 7.

Initially the target range is calculated without echo 0 as time reference. As shown by the correlation in Fig. 6, the time delay of the *echo*-0 is 5 µs, while *echo*-1 is 13 µs. The measured distance for target 1 is 1,950 m. The results are certainly not in accurate to simulated target distance.

Secondly, the range is calculated by considering the direct transmission signal as time reference. The *echo*-0 is detected and shifted to zero time reference as shown in Fig. 8. The *echo 0* is recognized as the first echo appeared in received signal, fortunately the direct transmission is from short range and come earlier than other echo signals.

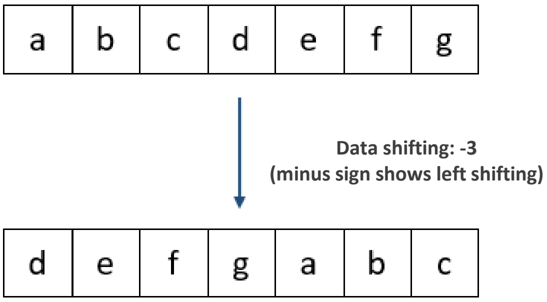

Fig. 8 Data shifting process.

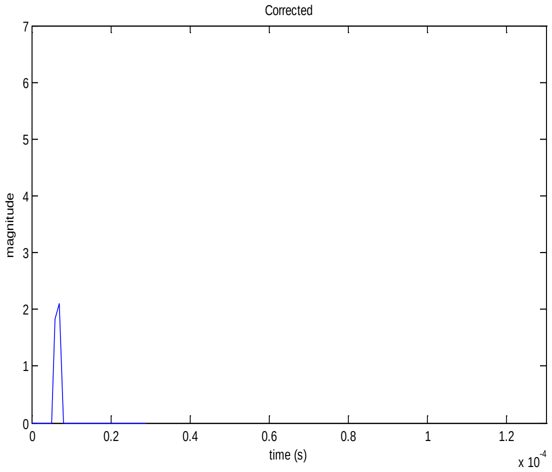

Fig. 9 Corrected echo signal for single target implementation.

After shifting process, the target distance is calculated. From the process, the measured distance was 1,200 m. Fig. 9 shows a correction results graph in the implementation of the one target distance detection using USRP.

The distance measurement test from USRP receiving signal and simulated target echo were conducted for 30 times. From 30 time tests, the success rate of correctly measured distance was 100%. This shows that the method of making *echo*-0 as a reference is successfully mitigate the random delay problem.

The second validation is by assuming two targets produce echo in the radar receiver, so received signal is the sum of three signals, i.e. *echo*-0 which is a direct received signal from radar transmitter; *echo*-1 is an *echo*-0 signal that has been delayed by $\Delta t1$; and *echo*-2 which is an *echo*-0 that has been delayed by $\Delta t2$. Each time delay represents r_1 and r_2 distances, respectively.

Simulated received signal for two targets at GRC is shown in Fig. 10. Delay time of $\Delta t1$ and $\Delta t2$ set in *echo*-1 and *echo*-2 are 8 µs and 16 µs, respectively, representing target range of 1,200 m and 2,400 m from radar.

In the measurement campaign, the time difference between transmitted signal and *echo*-0 is 1.26 ms, with *echo*-1 is 6 µs, and with *echo*-2 is 14 µs. Time delay experienced by *echo*-0 is seemed greater than *echo*-1 and *echo*-2. This is actually caused by the high processing delay that close to the pulse repetition period, so the echo signals are arrived in the processing windows of the next pulse. Correlation results in two-target implementation are shown in Fig. 11.

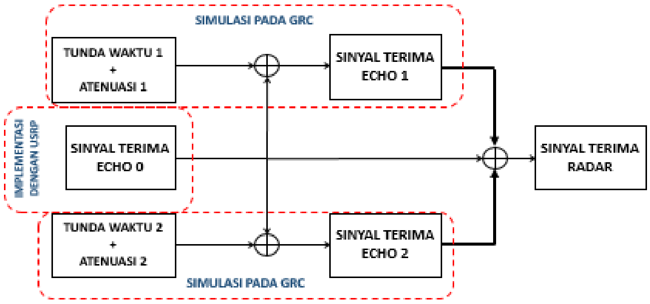

Fig. 10 Received signal forming of two targets at GRC.

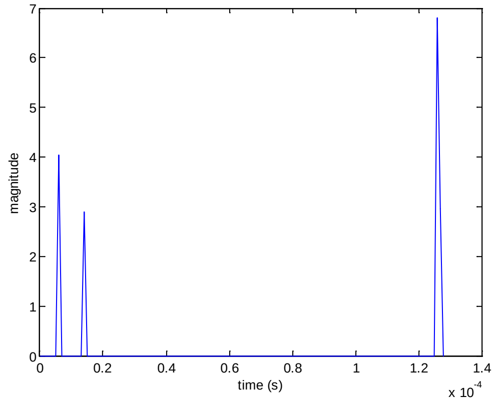

Fig. 11 Correlation results on two-target implementation.

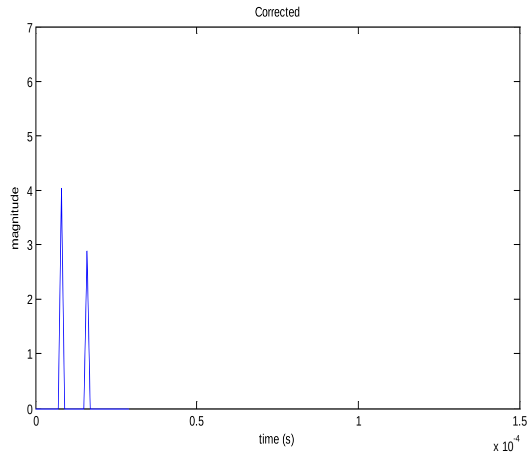

Fig. 12 Correction results for the two targets implementation.

When the range calculation was conducted without time reference correction, it obtains target 1 was detected at the distance of 900 m and target 2 was at a distance of 2,100m which disagree to the distance of simulated targets. The reference correction was made by shifting the peak position from *echo*-0 to position t = 0 and be utilized as a reference to calculate the *echo*-1 and *echo*- 2. The corrected results are shown in Fig. 12.

After correction, the calculation results are 1,200 m and 2,400 m. From the results of 30 times repeated test, the first target is detected with 100% correct results, while second target detection suffers 6.7% error or two of 30 tests are detected in wrong distance. However, these results are still acceptable because it gives 93% correct distance of second target.

The distance calculation error in the second target was 150 m from the exact distance. The measured distance was 2.550 m, while the distance should be 2,400 m. Radar resolution was 150 m equivalent to a sampling period in signal processing. This error is probably caused by the shift of echo signals due to noise or lag of clock synchronization between USRP in transmitter and receiver.

VI. Conclusion

The paper describes the implementation of USRP that is programmed by using GRC for to test it functionality as pulse radar and measure the processing delay time for pulse radar. The measurement campaign shows the appearance of random time delay. The average time delay is 0.0625 ms with a standard deviation value of 0.053 ms. The higher variability of random delay caused difficulty on ranging process of pulsed radar with USRP. A solution to mitigate this delay problem is also implemented by transmitting Barker Code with 128 bits in length. The delay between the transmitted and received signals can be evaluated from the correlation process between the radar transmitted signal and received signal. Then problems with random time delay in this system implementation can be overcome by using direct reception from the transmitting antenna to the receiving antenna as a reference. The result shows the target is successfully detected but the second target suffers from 6.7% measurement error after the correction of time reference.

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