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Sampling Deviation Real-Time Calibration Method for Wideband Simulator

Song Bingbing*[1], Pan Minghai[2], Hu Xiaohua[3]
Key Laboratory of Radar Imaging and Microwave Photonics Ministry of Education Department, Nanjing University of Aeronautics and Astronautics, 29 Yudao St., Nanjing, 210016, China
*Corresponding author, e-mail: coldicesong@139.com[1], panmh@nuaa.edu.cn[2], huxh1982@126.com[3]

Abstract

Hardware-in-the-loop simulation is an efficient method for research on radar system.Ttarget's echo which offered by the simulator should be synchronized with radar on frequency, time, and range bin. However, because simulator needs to take into account of the requirements of various types of radar, it is difficult to make the clock of simulator synchronized with the clock of radar. To solve the problem, synchronous sampling deviation model is established. Influence of sampling deviation on imaging is analyzed. An engineering method is put forward to eliminate the sampling deviation. This method not only provides a reference for simulation system, but also provides a reference for the design of radar system.

Keywords: *Synchronous Sampling Deviation, Real-Time Calibration, Hardware-in-The-Loop Simulation*

1. Introduction

Coherent radar means that transmitting signal of radar system, local oscillator, coherent oscillation, trigger pulse of timer should be offered by the same reference clock. The phase among those signals should be fixed. Coherence is the foundation to achieve the frequency hopping technology and linear frequency modulation technology. Pulse-Doppler radar which is widely used is coherent radar [1].

One of conditions for Pulse-Doppler radar's signal processing is making the sampling signals coherent among pulses. Some constraints are required for sampling parameters in [2],[3]. It is required that the sampling clock and the trigger should synchronize to the pulse repetition frequency (PRF). The synchronization precision will directly affect the performance of signal processing [4].

For Pulse-Doppler radar, frequency-stepping radar and pulse-compression radar, in order to meet the requirement of spectrum analysis and image processing, it is required to maintain coherence among pulses. For coherent radar, to maintain the coherence among pulses, sampling time interval between the nth sample point of the i-th pulse and the nth sample point of the i+1-th pulse should be the pulse repetition time [3].

For universal signal acquisition system, it is easy to meet the requirements of coherent among pulses when the sampling clock is offered by the radar system. This sampling method is called external synchronous sampling. If radar system does not provide a sample clock for acquisition system by itself, an internal clock in the acquisition system is used. This sampling method is called internal synchronous sampling. When the internal synchronous sampling method is used, it is difficult to maintain coherence among pluses, because the internal clock of acquisition system need to give consideration to various pulse repetition frequency [5].

Hardware-in-the-loop simulation is an efficient method for research on radar system. The accuracy of echo simulation has a direct impact on the effectiveness and accuracy of the processing results of radar system [6]. When simulating echo signal of radar, target's echo should be synchronized with radar on frequency, time, and range bin. Frequency synchronization requires that the same clock source should be shared between simulator and radar; time synchronization requires that the simulator's output is synchronized with PRF of radar; range bin synchronization requires that the range bin interval of simulator is the same as that of radar, or it is some multiple of the range bin interval of radar. However, in actually, simulator needs to take into account of the requirements of various types of radar, or needs to take into account the requirements of various types of PRF. It is difficult to make the clock of simulator same as the clock of radar. It will reduce the synchronization accuracy between

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sampling frequency and PRF when PRF is sampled by simulator. It will destroy the coherence among pulses. It will have an influence on signal processing, such as SAR imaging.

In this paper, synchronous sampling deviation model is established, and influence of sampling deviation on imaging is analyzed. On this basis, an engineering method is put forward to eliminate the sampling deviation. This method not only provides a reference for the design of simulation system, but also provides a reference for the design of radar system.

2. Description of the problem

Assume that the pulse repetition interval (PRI) of radar's transmitting signal is Tr, and the sampling frequency for simulator is Fs (Fs = 1/Ts). On the basis, the number of sampling points in a PRI is Np = Tr/Ts. If the sampling frequency is not an integer multiple of the pulse repetition frequency, Np is not an integer. It will destroy the coherence among pluses and will affect the radar imaging. Detailed theoretical analysis is completed in [4],[5]. In this paper, analysis conclusion is quoted directly.

The IF echo signal of the radar can be expressed as

$$s_{IF}\left(t\right) = rect\left(\frac{t}{\tau}\right)\exp(2\pi f_0 t) \tag{1}$$

The echo signal which is generated by simulator and received by radar is

$$s_D\left(\tau(i,n)\right) = rect\left(\frac{\tau(i,n) - R/c}{T}\right)\exp[j2\pi(f_0 + f_d)t] \tag{2}$$

where $\tau(i,n)$ is the time for the nth sample point of the i-th pulse.
Let $\tau(i,n) = iTr + nTs + \delta_{t_i}$, then

$$s_D\left(i,n\right) = rect\left(\frac{iTr + nTs + \delta_{t_i} - R/c}{T}\right)\exp[j2\pi(f_0 + f_d)(iT_r + nT_s + \delta_{t_i})] \tag{3}$$

If the sampling frequency is not an integer multiple of the pulse repetition frequency, δ_{t_i} changes along with the number of pulse, and it changes periodically. The minimum change cycle is M, and M can be given by the following equation:

$$MTr = NTs$$

Suppose $i = kM + m$, then

$$\tau(i,n) = (kM + m)Tr + nTs + \delta_{t_i} \tag{4}$$

So, the signal for the nth sample point of the i-th pulse can be expressed as

$$s_D\left(i,n\right) = \exp[j2\pi(f_0 + f_d)((kM + m)Tr + nTs + \delta_{t_i})] \tag{5}$$

In general, the most obvious way to implement the coherent processing is calculating the discrete Fourier transform (DFT) of the output of the nth sample point per pulse [7-9]. The result for DFT can be expressed as

$$S(f,n)=\sum_{i=-\infty}^{+\infty} s_D(i,n)\exp(-j2\pi fiT_r)$$
$$=\exp(j2\pi f_d nT_s)\bullet\frac{1}{T}\sum_{k=-\infty}^{+\infty} A(k,f_d)X_c(f-kf_r/M) \tag{6}$$

Where

$$A(k,f_d)=\frac{1}{M}\sum_{m=0}^{M-1}\exp(j2\pi(f_0+f_d)\delta_{t_i})\exp(-jkm\frac{2\pi}{M}),\quad X_c(f)=2\pi\delta(f-f_d)$$

The result of above shows that the period of S(f,n)'s frequency spectrum is Fr (Fr=1/Tr). There are M lines in each cycle. Interval of lines is Fr/M. The maximum peak correspond to the Doppler shift (fd) of the echo. The location for the k-th line of the frequency spectrum is fd+kFr/M. However, the Doppler shift should be fd in theory. It is caused by no-uniform sampling. No-uniform sampling destroys the coherence among pulses, and leads to several spectrum lines appear [4, 5].

According to the analysis, simulation is completed. The parameters for simulation are as follows. The transmitting signal of radar is linear frequency modulation signal (LFM); the bandwidth of the signal is 100MHz; the PRF is 42KHz; the pulse width is 3.2us; the velocity of the radar is 3500m/s; the carrier frequency is 35.35GHz; the height of the radar is 40Km; and the sampling clock is 150MHz. The results of the simulation are shown in Figure 1. Figure 1(a) shows the coherent accumulation result for the situation that the sampling deviation is eliminated; and Figure 1(b) shows the result caused by sampling deviation.

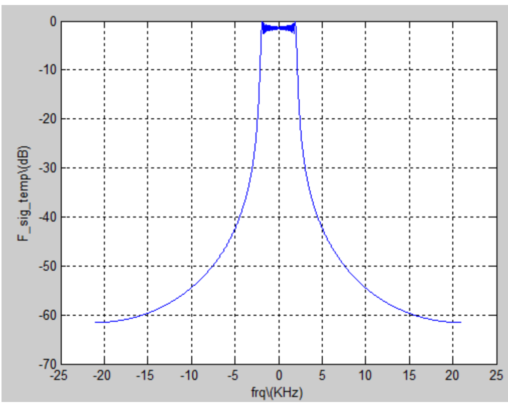


Figure 1(a). Coherent accumulation result for that the sampling deviation is eliminated

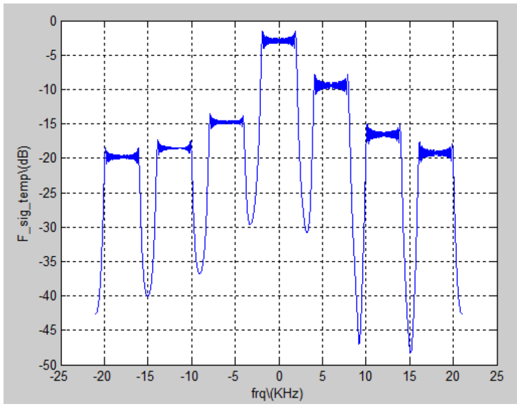


Figure 1(b) Coherent accumulation result caused by sampling deviation

3. Influence of sampling deviation on imaging

According to the analysis of section II, the baseband signal which is received by SAR can be expressed as:

$$s_D(i,n)=rect\left(\frac{iTr+nTs+\delta_{t_i}-R_t/c}{T}\right)\exp[j\pi K_r(iTr+nTs+\delta_{t_i}-R_t/c)^2]$$
$$\exp(-j2\pi R_t/\lambda)\exp(j2\pi f_0\delta_{t_i}) \tag{7}$$

If $\delta_{t_i}=0$, the sampling frequency is an integer multiple of the pulse of the pulse repetition frequency, the sampling deviation is not exist, SAR imaging can be completed easily, and the image quality is good. However, if $\delta_{t_i}\neq 0$, the sampling deviation appears, and the coherence among pulse is destroyed. The image quality goes worse. The influence on imaging will be focused on in this part.

The second-order approximation model of range is introduced [10]:

$$R_t = R_0 - \lambda(f_{dc}t + \frac{1}{2} f_r t^2) \quad (8)$$

R_0 is the initial round-trip range, f_{dc} is Doppler center frequency, f_r is Doppler rate.

Take the model into $s_D(i,n)$:

$$s_D(i,n) = rect\left(\frac{iTr + nTs + \delta_{t_i} - R_t / c}{T}\right) \exp[j\pi K_r (iTr + nTs + \delta_{t_i} - R_t / c)^2] \quad (9)$$
$$\exp(-j2\pi R_0 / \lambda) \exp(j2\pi f_{dc}t + j\pi f_r t^2) \exp(j2\pi f_0 \delta_{t_i})$$

Using the RD imaging algorithm, the signal after pulse compression in range dimension will be get:

$$s_R(i,n,t) = \sin c\left[B(\frac{iTr + nTs + \delta_{t_i} - R_t / c}{T})\right] \exp(-j2\pi R_0 / \lambda) \quad (10)$$
$$\exp(j2\pi f_{dc}t + j\pi f_r t^2) \exp(j2\pi f_0 \delta_{t_i})$$

where δ_{t_i} is the deviate time for sampling, and it is periodic. Its period is M. In addition, $|\delta t_i| < f_s$. As can be seen from the above analysis, the effects on imaging are as follows:

(1) The deviation would lead to position offset of the maximum peak in range dimension. δ_{t_i} is periodic, so the position of the maximum peak appears jitter. Because $|\delta t_i| < f_s$, the jitter is limited in a range unit.

(2) Because of the additional(1) After pulse compression in range dimension, there is a deviation (δ_{t_i}) at the maximum peak. phase ($\exp(j2\pi f_0 \delta t_i)$), pulse compression in azimuth dimension will be affected.

4. A method for eliminating the sampling deviation in real time

From the above analysis we can see that the influence of sampling deviation on signal processing cannot be ignored. It is necessary to eliminate the sampling deviation. In this paper, a method is put forward to solve this problem. Through the analysis of part 2, the period of δ_{t_i} is determined by the relationship between the sampling clock of simulator and pulse repetition frequency of radar. If the sampling clock and pulse repetition frequency are already given, the period of δ_{t_i} can be get easily. However, because the initial phase of the sampling clock is random and the sampling time is random when simulator powers up, it is difficult to eliminate the sampling deviation. If the sampling time is fixed when simulator power up every time, it is easily to compensate the sampling deviation by using a group of fixed parameters.

There is a fixed relationship between sampling frequency and pulse repetition frequency: $MTr = NTs$, so the number of sampling points in a pulse repetition interval varies in a cycle. The number of sampling points in a pulse repetition interval can be expressed as $N_p = T_r / T_s$. Because of the sampling deviation, N_p is not an integer. $frac(N_p)$ is the fraction of N_p. There is one more sample every M PRIs if $frac(N_p) < 0.5$, and one less sample every M PRIs if $frac(N_p) > 0.5$ [4]. The PRI whose samples' number changes can be found easily. If the next PRI is considered as the first PRI when simulator powers up, the initial phase of the sampling clock is fixed every time. On the basis, sampling deviation can be compensated easily by a group of fixed parameters. The implementation diagram is shown in Figure 2.

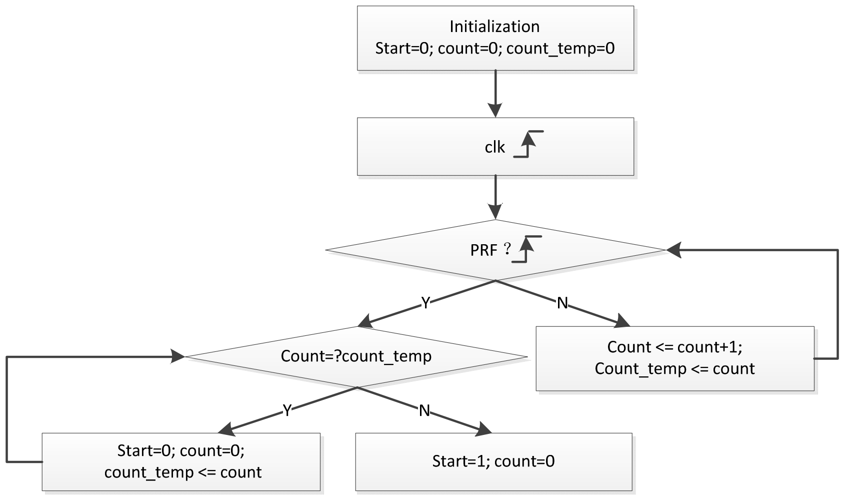


Figure 2. The implementation diagram for finding the first PRI

If the initial phase of the sampling clock is fixed every time, the deviation that should be compensated for every PRI is fixed too. If the period of δ_{t_i} is M, suppose $\delta_{t_1}=0$, $\delta_{t_2}=\delta_t$, $\delta_{t_3}=2\delta_t$, $\delta_{t_4}=3\delta_t$, $\cdots$, $\delta_{t_M}=(M-1)\delta_t$. The delay of the sampling clock for the first PRI is $(M-1)/(M*T_s)$, for second PRI is $(M-2)/(M*T_s)$, for the third PRI is $(M-3)/(M*T_s)$, and for the (M-1)-th PRI is $1/(M*T_s)$. The delay of the sampling clock for the M-th PRI is zero. In this way, it is ensure $\delta t_1=\delta t_2=\delta t_3=\cdots=\delta t_M=(M-1)/(M*T_s)$.

Because the delay is less than one clock cycle, it cannot be completed by using system clock. The delay can be carried out by the phase shifting module in FPGA. Phase shift precision for FPGA can achieve to 1/56 cycle of Mixed-Mode Clock Manager's VCO, so the minimum of δ_{t_i} that can be achieved is T/56 of VCO.

5. Simulation and verification

Hardware-in-the-loop simulation system which consists of radar and echo simulator is an effective means to verify the compensation method and analysis the influence of the sampling deviation. The system is a useful supplement to the theoretical analysis and digital simulation. The construction of the hardware-in-the-loop simulation system is as Figure 3.

The system works at Ka wavelength. Its bandwidth is 100MHz. The system consists of microwave down-conversion unit, microwave up-conversion unit and signal processing unit etc. Microwave down-conversion unit receives the RF signal, and moves the frequency spectrum from Ka wavelength to S wavelength. The Microwave up-conversion unit converts the baseband echo to Ka wavelength, filters harmonic wave, and controls the power of output. The RF signal from Microwave up-conversion unit will be poured into the receiver of the radar. Signal processing unit samples IF signal, changes IF signal to zero intermediate frequency, generates echo of baseband using convolutions.

To verify the impact of sampling deviation, set the work parameters of the system as follows: the transmitting signal of radar is LFM; its bandwidth (BW) is 100MHz; the PRF is 42KHz; the pulse width (PW) is 3.2us; the velocity of the aircraft which carries the radar (Vt) is 3500m/s; the carrier frequency of radar (Fc) is 35.35GHz; the height of the aircraft (H) is 40Km; and the sampling frequency of simulator (Fs) is 150MHz. Because N=Fs/PRF is not an integer, the sampling deviation appears, and the coherence among pulse is destroyed. The image quality goes worse.

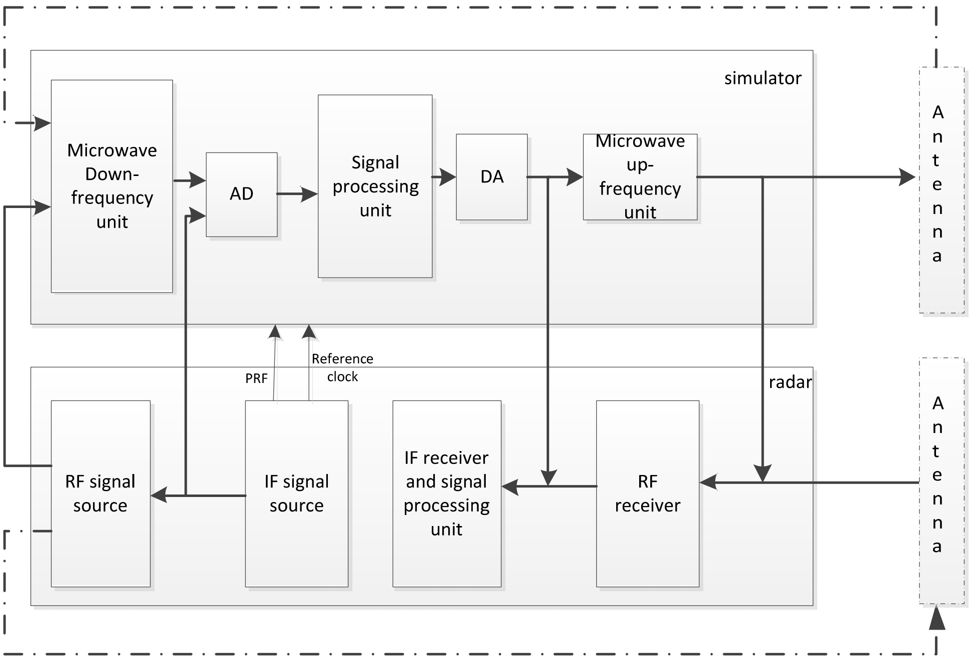
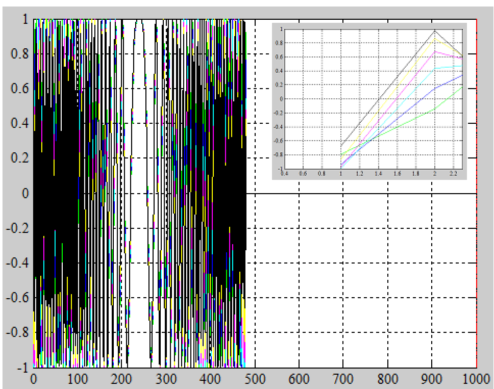
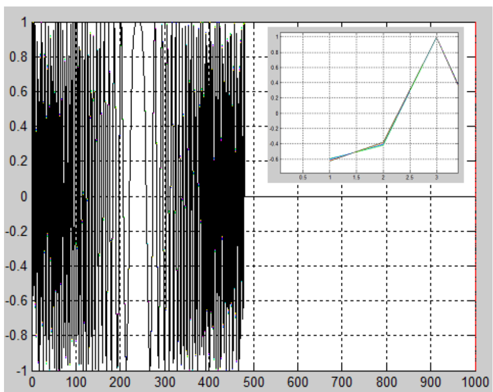


Figure 3. Block diagram of the construction of hardware-in-the-loop simulation system

In experiment, the transmitting signal is injected into the simulator, and is converted to low intermediate frequency. At the same time, the power is adjusted by the auto gain control unit (AGC) in microwave down-frequency unit to make sure the analog-to-digital converter can get the best SNR (signal to noise ratio). Then, the signal is sampled by analog-to-digital converter. The sampling frequency is not an integer multiple of the pulse repetition frequency, so the sampling time is not fixed when simulator powers up. The phase of signal is random. Signals of M pulses with sampling deviation and signals that are corrected are shown in Figure 4.



(a)



(b)

Figure 4. Signals of M=7 pulses; a) with sampling deviation; b) signals that are corrected

The imaging results that with sampling deviation and the results that deviations are corrected are shown in Figure 5. The results are consistent with the analysis in part 3.

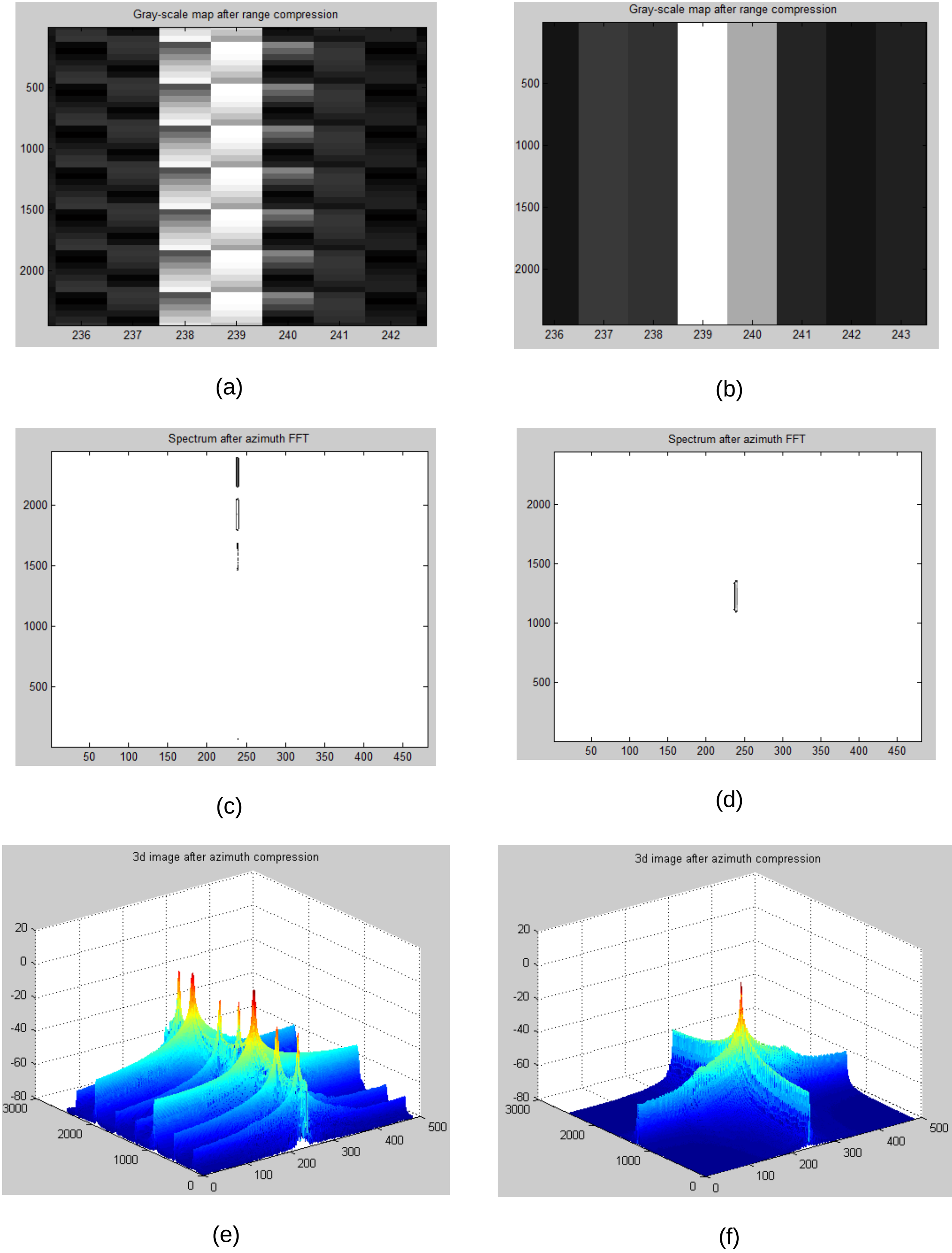


Figure 5. The imaging results that with sampling deviation and the results that deviations, gray-scale map after: (a). Gray-scale map after range compression with sampling deviation, Gray-scale map after range compression which deviation is corrected, (c). Spectrum after azimuth FFT with sampling deviation, (d). Spectrum after azimuth FFT which deviation is corrected, (e). 3D image after azimuth compression with sampling deviation, (f). 3d image after azimuth compression which deviation is corrected

The simulation results show that the deviation leads to position of target appear jitter in range dimension. The azimuth compression is greatly affected by the presence of $\exp(j2\pi f_0\delta_{t_i})$. Because of the periodic of δ_{t_i}, the peak after azimuth compression also appears periodic variation and defocus appears. It may cause false alarm. Using the method mentioned in this paper, the influence on imaging for sampling deviation is eliminated effectively. This method has a high value in the field of engineering.

6. Conclusions

In this paper, problems caused by sampling deviation are studied, the sampling deviation model is established, and influence of sampling deviation on imaging is analyzed. Because of the sampling deviation, the peak after range compression appears jitter, and the azimuth compression is greatly affected by the presence of the additional phase. Because of the periodic of the sampling deviation, the minor lobe increases sharply, and defocus appears. On this basis, an engineering method is put forward to eliminate the sampling deviation. This method not only provides a reference for simulation system, but also provides a reference for the design of radar system.

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