The Research of Velocity Compensation Method Based on Range-Profile Function

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Abstract

In the high-resolution radar imaging system, step-frequency radar signal is very important in getting the high-resolution range-profile, which can be used for target's detection and recognition. However, target radial velocity will produce many problems, therefore, moving-targets imaging is a bottleneck for step-frequency radar signal. In this paper, an effective motion compensation methods is presented, which is based on the function of Range-profile Contrast. The numeric simulation indicates that this method is effective, which can estimate the target's velocity in real-time, and it is easy to be used in engineering project. After target's motion compensation, the high-resolution range-profile will be much better than that is used to be, which can be used for the detection, recognition and ranging of moving targets..

Keywords: Step-Frequency; Range-profile; Velocity Estimation; Motion Compensation; Range-profile Contrast

1. Introduction

In radar system, the pulse compression signals are widely used in getting the high-resolution range-profile and it is called as HRRP in short. Step-frequency (SF) radar signal is one of the most important pulse compression signal, which is well illustrate in reference [1-3]. For the processing of step-frequency radar signal, the velocity between target and radar will make the distortion of HRRP. Therefore, for the non- cooperative targets, the step-frequency radar signal has a serious problem of Range-Doppler coupling [5].

The impact of Range-Doppler coupling can be eliminated or relieved target's by motion compensation. Suppose, the target's velocity is precisely estimated, the phase terms which is caused by the motion of target, can be compensated by removing it. Many motion compensation methods are presented based on velocity estimation. In reference [6, 7], based on time domain and waveform entropy, two motion compensation methods are presented, however they have low estimation accuracy in low SNR, and they are only effective for moving targets with low velocity. In reference [8], based on SF and Pulse Doppler system, an effective method of motion compensation is presented; numeric simulation shows that this new method has higher compensation accuracy and better anti-noise performance. But it will increase the calculation complexity of radar system. Until now, except for those methods mentioned above, other effective motion compensation methods have been also presented, for example in the reference [9-11], which have gotten much better compensation result.

But, in common, they need much larger computation complexity and calculation amount, meantime they are not easy to be used in project application.

As discussed above, in low SNR, the motion compensation method of moving targets is still a key problem for SF signal. Furthermore, the application in project also should be considered. In this paper, based on the analysis of range-profile, an effective motion compensation method is presented. Numeric simulation indicates that this method has a high estimation accuracy and low calculated amount than that used to be, which is easy to be used in engineering project application.

2. The Range-Doppler Coupling of SF Radar Signal

Step-frequency radar signal is a pulse sequence that the carrier frequency increased by the fixed step length, which is shown in formula (1).

$$u(t) = \frac{1}{\sqrt{NT_1}} \sum_{i=0}^{N-1} rect\left(\frac{t - iT_r}{T_1}\right) \exp j2\pi(f_0 + i\Delta f)t \tag{1}$$

Where, f_0 is the centre frequency, T_1 is the pulse width, T_r is the pulse repetition cycle, Δf is the step-frequency value, N is the pulse number.

Suppose, the distance between radar and target is R_0, after I/Q frequency mixing of double channel, we can get the complex envelop output of echo signal:

$$G_i = \exp\left[-j2\pi f_i\left(\frac{2R}{c}\right)\right] = \exp(j\psi_i) \tag{2}$$

Suppose, the target is moving, the phase term of target echo signal can be expressed as follows:

$$\psi_i = -2\pi f_i \frac{2(R - vt)}{c} \tag{3}$$

Suppose, v is relatively radar target of radial velocity, t is time, which is shown as follows:

$$t = iT_r + \frac{T_1}{2} + \frac{2R}{c} \tag{4}$$

Introducing the formula (4) into (3), the formula (5) can be gotten

$$\psi_i = \underbrace{\frac{2f_0 R}{c}}_{const} + \underbrace{\frac{2nR\Delta f}{c}}_{f_R} - \underbrace{\frac{2f_0 vT_r n}{c}}_{f_d} - \underbrace{\frac{2v\Delta f T_r n^2}{c}}_{Spread} \tag{5}$$

The Eq.(5) reveals the special properties of SF radar signal. The first term represents a constant phase migration. The second term is produced by the product of frequency. The third term f_d in Eq. (5) is a linear phase term, which represents the Doppler frequency migration due to target motion. The processing of IDFT mistakes the Doppler frequency as a frequency migration due to range and thus results in the shifting of target range from its true range.

According to the literature [5], suppose, in order to perfectly compensate LPT, the sustainable error of distance measurement is half of range resolution of SF signal, which is shown as follows:

$$\Delta R = \frac{\Delta r}{2} = \frac{c}{4N\Delta f} \tag{6}$$

Then, the estimation accuracy of target speed must satisfy Eq. (7).

$$\left|\Delta v\right|_{\text{LPT}} \leq \frac{c}{2}\left(\frac{\Delta f}{f_0}\right)\left(\frac{1}{T_r}\right)\left(\frac{1}{N\Delta f}\right) = \frac{c}{4f_0 N T_r} \tag{7}$$

The fourth term 'Spread' in Eq. (5) is a quadratic phase term, which causes by the frequency spread. According to the literature [5], suppose, the sustainable change of quadratic phase term satisfies the following requirement.

$$2\pi \frac{2N\Delta f\left|\Delta v\right|_{\text{QPT}}}{c} N T_r \leq \frac{\pi}{2} \tag{8}$$

Then, the estimation accuracy of target speed must satisfy Eq. (9)

$$\left|\Delta v\right|_{\text{QPT}} \leq \frac{c}{8N^2 \Delta f T_r} \tag{9}$$

From the above analysis we can know that, target motion is the main reason of range-profile variation for step-frequency. Therefore important feature of the target motion can be extracted by analyzing the characteristics of the range-profile.

3. Velocity Estimation Method based on Range-profile Contrast

The contrast function of range-profile is the ratio of the goal and the surrounding environment brightness difference. It is a measure of waveform focus degree. In the range-profile, the defocus brought by movement will make the amplitude of scattered points around the mean and the contrast ratio is very low. However, the degree of the waveform focusing can be improved by motion compensation.

By the concept of contrast function, it is easy to understand that contrast function is the degree of disorder, the greater contrast function value is, and the lower disorder range-profile is. And when the range-profile is focused, the contrast function will have the maximum value. The range-profile contrast function is defining as follow:

The contrast function of range-profile can be defined as following:

$$C_1(v) = \max\{H\} \tag{10}$$

Or

$$C_2(v) = \frac{\sqrt{A\left\{\left[H - A\{H\}\right]^2\right\}}}{A\{H\}} \tag{11}$$

Or

$$C_3(v) = \frac{\sqrt{A\left\{\left[H^2 - A\left\{H^2\right\}\right]^2\right\}}}{A\left\{H^2\right\}}$$ (12)

The steps of Maximum range-profile contrast method are shown as follows.

① calculating the motion compensation factor by the initial estimated value of velocity:

$$p_i = \exp\left[-j2\pi\left(f_0 + i\Delta f\right)\frac{2v_0 i T_r}{c}\right]$$ (13)

② compensating the echo signal:

$$G_i^{'} = G_i p_i = \exp\left[-j2\pi\left(f_0 + i\Delta f\right)\frac{2\left(R_0 - \Delta v i T_r\right)}{c}\right]$$ (14)

③ making the inverse Fourier transform for compensated signal:

$$h(l) = \sum_{i=1}^{N} G_i^{'} \exp\left[j2\pi\frac{li}{N}\right]$$ (15)

④ calculating the range-profile contrast function according to formula (11).

⑤ confirming the next estimated velocity value by a certain optimization method and repeat the steps till the maximum value of range-profile entropy is found, and then the final estimated velocity can be gotten.

4. The Simulation of Estimation Result

Supposing the target model is a rigid body (the radial velocity of every scatters are the same), which is shown in Figure 1. The target is composed by four strong scattering points which are parted to $7\Delta r$, $3\Delta r$ and $6\Delta r$ in sequence and noted as A, B, C, and D respectively. The normalized scattering intensity ratio is $1:10:6:8$, the radial distance is $1\mathrm{km}$. The parameters of the step-frequency radar signal transmitted by radar is as follows: transmitting frequency $f_0 = 94\,\mathrm{GHz}$, step value $\Delta f = 4\,\mathrm{MHz}$, pulse width $T = 100\,\mathrm{ns}$, repeat cycle $Tr = 20\,\mathrm{u}$, pulse number $N = 128$, $\Delta r = \frac{c}{(2N\Delta f)} = 0.3\,\mathrm{m}$

(The parameters are adopted in all the simulation below).
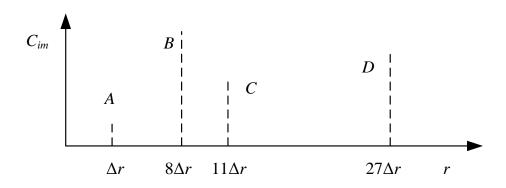
Figure 1. Point of the strong scattering target

Figure 2 is the velocity estimation characteristic figure which is drawn by the formula (11). From the figure we can know that the contrast function of range-profile have some local maximum points, which requires optimizing search algorithm to ensure jump out of the local maximum point and converges to the true value.

The Figure 3 shows the velocity estimation error with different SNR through 1000 times' Monte Carlo simulation experiments. From the picture we can know that no matter how high the SNR of echo is, the maximum range-profile contrast ratio can't achieve high accuracy of compensation. Therefore, it can only be used to compensate for coarse profile. And, we can't achieve better compensation effect because the standard deviation of the velocity estimation errors and the discrete degree of the velocity estimation error is big. According to Figure 4, the velocity estimation error also proves the above conclusion.
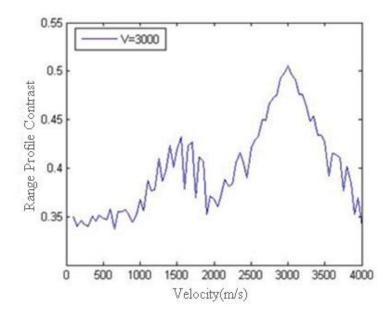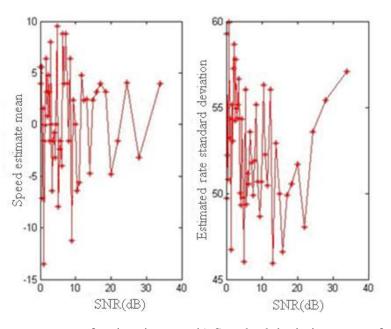

Figure 2. The characteristic figure of elocity estimation

a) The mean error of estimation   b) Standard deviation error of estimation

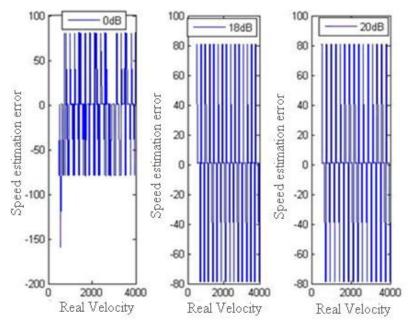**Figure 3. Velocity estimation error with the signal-to-noise ratio variation**

Figure 4. The error chart of elocity estimation

5. Conclusions

According to the discussion above, we can get several conclusions as follows:

(1) This velocity estimation method has the global optimal value and local optimal value, therefore the initial value and optimization search method will make a great influence on the estimate effect.

(2) The estimation effect of the maximum range-profile contrast method can only be used for a coarse estimate in low SNR, but when the SNR is increasing, the accuracy of estimation become better.

Based on the discussion above, maximum range-profile contrast method is suitable for the engineering application, and the following research is looking for simple initial velocity estimation algorithm. It should be ensure to choose the estimated range which can cover the true value, and do not contain local optimal value. Then, the suitable evaluation function and optimization search algorithm should be given. At the same time, it must be reduce the computational complexity and improve the velocity estimation precision.

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