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HPRF pulse Doppler stepped frequency radar

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Stepped frequency radar is a well known scheme to generate high range resolution profile (HRRP) of targets. Through appropriate radar parameter design, the radar enables both unambiguous velocity measurement and high resolution ranging within a single dwell in a high pulse repetition frequency (HPRF) mode. This paper analyzes in detail the design principle of the HPRF stepped frequency radar system, the solution to its ambiguity issue, as well as its signal processing method. Both theoretical analysis and simulation results demonstrate that the proposed radar scheme can work independently to solve the problem of motion compensation, and is therefore highly applicable to many new types of radar.

DFT, HPRF, pulse Doppler radar, stepped frequency radar

1 Introduction

The stepped frequency (SF) radar is a kind of high range resolution (HRR) radar. It transmits a series of narrowband pulses, which are stepped in frequency from pulse to pulse and form a burst that covers a wide bandwidth. SF radar requires only a narrow instantaneous receiver bandwidth and hence can tremendously reduce system complexity and cost. Figure 1[1] shows a schematic diagram of an SF radar system.

However, SF radar has the disadvantage of being very sensitive to target motion, which results in target range shift as well as echo spread in its HRRP, so motion compensation is needed for moving target processing[2−4]. Traditionally SF radar does motion compensation with target velocity information obtained under a narrow-band working mode of the radar or from outside, which makes the radar system fail to work independently.

The research results of this paper shows that, in the HPRF mode, through careful choice of radar design parameters, SF radar can achieve both unambiguous velocity measurement and high range resolution in a single dwell or burst, which enables the independent operation of the radar. For SF radar, the choice of signal processing methods is also important for radar performance. SF radar usually adopts IDFT method to obtain target HRRP[5], and alternatively it can also adopt DFT method. In this case, the SF radar can be seen as a pulse Doppler stepped frequency (PD SF) radar.

The concept of HPRF SF radar was first developed by Myers in 1996[6,7], with a specific imple-

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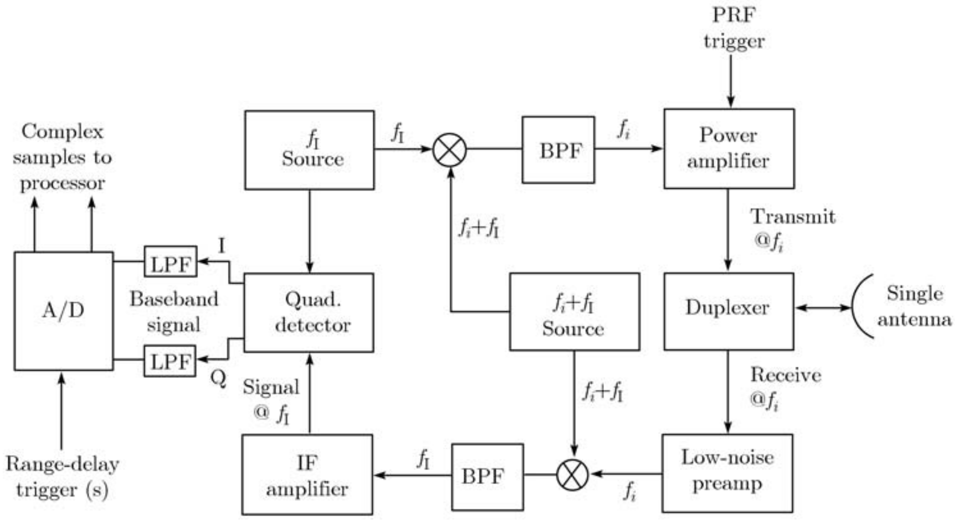

Figure 1 Schematic representation of a simple stepped frequency radar system[1].

mentation in engineering introduced. In this research, this radar scheme has been studied thoroughly, including system parameter design principle, its specific signal processing method, as well as solution to its ambiguity issues.

The remainder of paper is organized as follows: Section 2 is a thorough analysis of SF radar parameters. Section 3 introduces the signal processing method of HPRF SF radar. Section 4 studies HPRF SF radar's parameter design principle. Section 5 introduces the ambiguity issues of HPRF SF radar and their resolutions. In section 6, the processing procedure for HPRF SF PD radar is presented, and simulation results are given to justify the theoretical analysis. A summary of findings and conclusions is given in section 7.

2 Parameter analysis for HPRF SF radar

The performance of an SF radar system is basically determined by the choice of its system parameters. No matter which signal processing method is chosen, pulse bandwidth of B_τ is approximately equal to the frequency step Δf. This means that the range coverage of the radar is approximately equal to pulse duration of τ[8]. For static targets, the result is a correctly positioned HRRP of the target. For moving targets, the result is a circularly shifted HRRP of the target. However, in the HPRF mode, through careful choice of the radar design parameters, the radar can achieve both unambiguous velocity and high range resolution in a single dwell or burst.

In this section, some parameters that have close relationship with parameter design are analyzed in detail.

2.1 Receiver bandwidth B_{IF} of the radar system

2.1.1 Relationship among B_{IF}, pulse duration τ and frequency step Δf. Firstly, radar receiver's IF bandwidth B_{IF} should satisfy the matched filter condition

$$B_{\mathrm{IF}} \approx B_\tau. \tag{1}$$

To avoid overlapping, the HRRP coverage of $\frac{1}{\Delta f}$ for each range cell must be greater than or equal to its actual range coverage of τ[5], i.e.,

$$\tau \leqslant \frac{1}{\Delta f} \text{ or } B_\tau \geqslant \Delta f. \tag{2}$$

From eqs. (1) and (2), we have the following condition that must be satisfied:

$$B_{\mathrm{IF}} \approx B_\tau \geqslant \Delta f. \tag{3}$$

2.1.2 Relationship among B_{IF}, echo bandwidth δf, and PRF. For SF waveform with a frequency modulation slope $k = \frac{\Delta f}{T_r}$, the maximum echo bandwidth of the quadrature detector output is

$$\delta f = \frac{\Delta f}{T_r}\frac{2R_{\max}}{\mathrm{c}} = \Delta f \frac{R_{\max}}{\mathrm{c}T_r/2}. \tag{4}$$

where c is the velocity of light and $R_{\max}$ is the maximum target range. From eq. (3), we have the following conclusions:

• In low PRF (LPRF) mode, i.e., when there is no range ambiguity ($R_{\max} \leqslant \frac{cT_r}{2}$) and therefore $\delta f \leqslant \Delta f$, it is common for radar systems to be designed such that at $R_{\max} \approx \frac{cT_r}{2}$ (whilst maintaining enough average transmit power) and thus $\delta f \approx \Delta f$. In this case, B_{IF} is only restricted by eq. (3).

• In HPRF mode, i.e., when there exists range ambiguity, there is $R_{\max} > \frac{cT_r}{2}$ and then $\delta f > \Delta f$. In this case, if only a single receiver is required to cover the entire operating range, the receiver bandwidth must satisfy the condition $B_{\mathrm{IF}} \geqslant \delta f$. In addition, the restriction implied by eq. (3) means that the receiver bandwidth B_{IF} in the HPRF mode will increase in comparison to the case for the LPRF mode.

2.2 Range window of the radar system

When SF radar works in an HPRF mode, its working range usually satisfies $R_{\max} \gg \frac{cT_r}{2}$. Thus according to eq. (4), there is $\delta f \gg \Delta f$ for the echo bandwidth δf. If the receiver bandwidth B_{IF} is still chosen as $B_{\mathrm{IF}} = \delta f$ such that the receiver has to sample and process the whole echo bandwidth ($B_{\mathrm{IF}} \gg \Delta f$), then radar system's sampling rate and signal processing ability are essentially required to be the same. In this circumstance, the SF waveform has no more advantage over a Chirp waveform's processing bandwidth. Therefore a processing method similar to de-Chirp processing must be adopted for long distance case. This means that the receiver bandwidth B_{IF} should be the same as the echo bandwidth to be processed (i.e., the range window seen by the receiver). In this way the sampling rate and signal processing complexity can be reasonably controlled.

The range window size of $\delta R = \frac{\delta f}{\Delta f} \cdot \frac{cT_r}{2}$ needs to be set according to the specific requirement of different systems and is determined by the receiver bandwidth. Larger range windows imply shorter scanning time of the receiver for the whole range ambit and hence higher data rates. Thus the cost paid is the increase of receiver bandwidth and system implementation complexity. In addition, a large range window ($\delta f > \Delta f$) causes ambiguity ($\delta R > \frac{cT_r}{2}$) of the target. If the range window is given by$\delta R = n\frac{cT_r}{2}$, then there is $B_{\mathrm{IF}} \approx B_\tau \approx n\Delta f$ and the number of ambiguities in the range window will be n. Based on the previous analysis, the choice of range window size entails a tradeoff between radar's data rate and system implementation complexity.

2.3 Oscillator frequency of the radar receiver

HPRF SF radar may have an operating range far greater than its range window size. Thus a position adjustable range window is required for both tracking and searching functions of radar to cover the whole operating range. The range window can be positioned by adjusting the starting time t_0 of the oscillator's reference pulse as shown in Figure 2.

Using a stepped frequency master oscillator with a reference starting time t_0, the size of the range window is determined by t_0 and receiver bandwidth B_{IF} according to

$$-\frac{B_{\mathrm{IF}}}{2} \leqslant \frac{\Delta f}{T_r}\left(\frac{2R}{\mathrm{c}} - t_0\right) \leqslant \frac{B_{\mathrm{IF}}}{2}. \tag{5}$$

The frequency f_x produced by a target of range R_x in the range window is therefore

$$f_x = \frac{\Delta f}{T_r}\left(\frac{2R_x}{\mathrm{c}} - t_0\right). \tag{6}$$

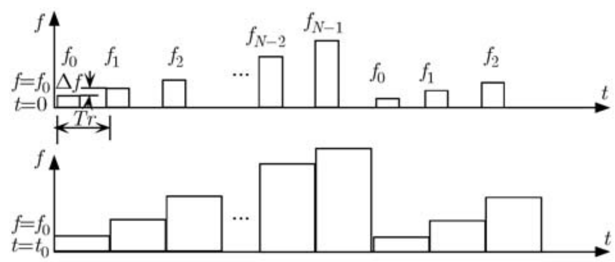

Figure 2 Frequency distribution of the transmission pulse and the reference pulse for the SF waveform.

3 Signal processing for HPRF SF radar

The choice of signal processing method is also important for the performance of an SF radar system. For HPRF SF radar, use the DFT method instead of traditional IDFT method enables it to measure a target's unambiguous velocity and obtain an HRR profile in a single dwell.

Consider the example of an SF waveform with a pulse repetition interval T_r, a pulse duration τ, a starting frequency f_0, a frequency step Δf and N steps in one burst or dwell. A sampling frequency is given by $f_\mathrm{s} = 1/T_\mathrm{s}$. The SF transmission signal may then be expressed as[5]

$$x(t) = \sum_{i=0}^{N-1} \mathrm{rect}\left(\frac{t - iT_\mathrm{r} - \frac{\tau}{2}}{\tau}\right) \mathrm{e}^{\mathrm{j}2\pi(f_0 + i\Delta f)t}, \quad (7)$$

where i is the index denoting a particular pulse within a burst.

3.1 Signal processing of static targets

For a static target with an initial radial range R_0, the receiver's output after quadrature detection is

$$y(t) = \sum_{i=0}^{N-1} \mathrm{rect}\left(\frac{t - iT_\mathrm{r} - \frac{\tau}{2} - \frac{2R_0}{\mathrm{c}}}{\tau}\right) \mathrm{e}^{-\mathrm{j}2\pi(f_0 + i\Delta f)\frac{2R_0}{\mathrm{c}}}. \quad (8)$$

The quadrature detection output of eq. (8) is sampled, normalized and transformed using DFT

$$y(i) = \sum_{i=0}^{N-1} \mathrm{e}^{-\mathrm{j}2\pi(f_0 + i\Delta f)R_0} \mathrm{e}^{-\mathrm{j}2\pi\, i\,\frac{l}{N}}. \quad (9)$$

Then the magnitude of DFT result is solved to give

$$|Y\,(k)| = \left|\frac{\sin\,(l+k)}{\sin\left(\frac{l+k}{N}\right)}\right|, \; k = 0,\ 1,\ 2,\ \ldots,\ N-1. \quad (10)$$

The physical meaning of the DFT processing is explained as follows: Each set of N samples from a range cell can be regarded as samples of a Chirp signal with pulse duration of NT_r and bandwidth of $N\Delta f$, and the effective sampling interval is T_r. The effective frequency modulation slope of the Chirp signal is given by $k = \frac{N\Delta f}{NT_r} = \frac{\Delta f}{T_r}$. The mixing of the oscillator reference signal with the echo signal in SF radar is essentially the same as dechirp processing of Chirp signal with a frequency modulation slope equal to k. The different frequency components in the output of the DFT represent targets at different ranges.

For static targets, the phase element in eq. (9) varies with i according to $-2\pi i\Delta f\frac{2R_0}{\mathrm{c}} = -2\pi\frac{\Delta f}{T_r}\frac{2R_0}{\mathrm{c}}iT_r$. This produces a frequency shift of $\frac{\Delta f}{T_r}\frac{2R_0}{\mathrm{c}}$ in the DFT output. It is important to note that it is a range coupled frequency shift caused by the target echo delay $\frac{2R_0}{\mathrm{c}}$. For static targets, the target range R_0 is obtained by solution of $l = \mathrm{Round}\left(-\frac{2R_0 N\Delta f}{\mathrm{c}}\right)$.

Since the frequency element $\frac{\Delta f}{T_r}\frac{2R_x}{\mathrm{c}} = k\frac{2R_x}{\mathrm{c}}$ is analyzed in DFT processing with a sampling interval of T_r, the unambiguous high resolution range after DFT processing is

$$R_\mathrm{u} = \frac{\mathrm{c}}{2\Delta f}. \quad (11)$$

The frequency resolution of the DFT therefore determines the range resolution and is given by

$$\Delta R = \frac{\mathrm{c}}{2N\Delta f}. \quad (12)$$

From the above analysis, it is clear that the unambiguous range and range resolution for DFT processing are identical to those with IDFT processing [1].

3.2 Signal processing of moving targets

For a moving target with a positive radial velocity v and an initial radial range R_0, the output of the quadrature detector can be expressed as[5]

$$y(t) = \sum_{i=0}^{N-1} \mathrm{rect}\left(\frac{t - iT_r - \frac{\tau}{2} - \frac{2R_0}{\mathrm{c}} + \frac{2vt}{\mathrm{c}}}{\tau}\right) \mathrm{e}^{-\mathrm{j}2\pi(f_0 + i\Delta f)\left(\frac{2R_0}{\mathrm{c}} - \frac{2vt}{\mathrm{c}}\right)}. \quad (13)$$

Here, the phase of the quadrature detector output in eq. (13) for each coarse range cell is given by

$$\begin{aligned}\varphi =& -2\pi(f_0 + i\Delta f)\frac{2(R_0 - vt)}{\mathrm{c}} \\ =& -2\pi f_0\frac{2R_0}{\mathrm{c}} + 2\pi f_0\frac{2v}{\mathrm{c}}iT_r \\ & -2\pi i\Delta f\frac{2R_0}{\mathrm{c}} + 2\pi i\Delta f\frac{2v}{\mathrm{c}}iT_r. \quad (14)\end{aligned}$$

Moving targets can also be processed with the DFT method. In this case, the signal processing can be analyzed from the perspective of a PD radar system. For a moving target with a positive radial velocity v and an initial radial range R_0, the components of the output phase expressed in eq. (14) can be rewritten as

$$2\pi \cdot f_0 \frac{2v}{\mathrm{c}} \cdot iT_r - 2\pi \cdot \frac{\Delta f}{T_r} \frac{2R_0}{\mathrm{c}} \cdot iT_r + 2\pi \cdot i\Delta f \frac{2v}{\mathrm{c}} \cdot iT_r. \tag{15}$$

After DFT processing, the different phase items in eq. (15) can be explained as follows:

- 1st order phase component $-2\pi \cdot \frac{\Delta f}{T_r} \frac{2R_0}{\mathrm{c}} \cdot iT_r$: This contains a range coupled frequency element $\frac{\Delta f}{T_r} \frac{2R_0}{\mathrm{c}}$ which is produced by the stepped frequency at a target range R_0 proportional to $\frac{\Delta f}{T_r}$.
- 1st order phase component $2\pi \cdot f_0 \frac{2v}{\mathrm{c}} \cdot iT_r$: Doppler frequency $f_0 \frac{2v}{\mathrm{c}}$ produced by the target velocity in the radial direction.
- 2nd order phase component $2\pi\Delta f \frac{2v}{c} iT_r$: This is the frequency coupling term and causes distortion of the target range profile [2,3,8].

Based on analysis presented in this section, the DFT output from the SF radar has two physical meanings: (i) a range value in the time domain with a period of $\frac{c}{2\Delta f}$, or (ii) a velocity value in the frequency domain with a period determined by PRF. If it is regarded as a range value in time domain, then the target velocity produces a coupled time shift for target ranging. If it is regarded as a velocity value in the frequency domain with period equal to that of PRF, then it produces a coupled frequency shift that displaces the target Doppler from its true position. When SF radar uses DFT method to process moving targets, it can be regarded as PD radar with a stepped carrier. The stepped carrier enables the radar to obtain PD measurement whilst at the same time achieving high range resolution.

4 Radar system's parameter design for HPRF PD SF radars

For SF radars in an HPRF mode, the maximum Doppler produced by a moving target usually satisfies $f_{d\max} < \frac{1}{T_r}$, and the radar system's working range satisfies $R_{\max} \gg \frac{\mathrm{c}T_r}{2}$, i.e., there is not any velocity ambiguity while at the same time range ambiguity does exist.

In an HPRF mode, depending on the requirements of the range window, different parameter values and signal processing methods may be adopted. They are listed as follows:

1) If the size of the range window is set as $\delta R = \frac{\mathrm{c}T_r}{2}$, then $B_{\mathrm{IF}} \approx B_\tau \approx \Delta f$, i.e., the system has no range ambiguity inside the range window. However, since $\tau \approx \frac{1}{\Delta f}$, the targets' RP is distributed throughout the DFT result. That is, for a static target at range R in the range window, the DFT peak position corresponding to the range coupled frequency shift $\frac{\Delta f}{T_r} \frac{2R}{\mathrm{c}}$ may be at any DFT bin depending on the range R. For moving targets, there is a Doppler frequency shift $f_0 \frac{2v}{\mathrm{c}}$ in addition to the range coupled frequency shift, which may result in cyclic shift of the DFT result. For this reason, in the HPRF mode, unambiguous velocity cannot be determined for systems with a range window $\delta R = \frac{\mathrm{c}T_r}{2}$. Here, the HPRF mode is effectively the same as LPRF mode.

2) If the size of the range window is set as $\delta R = n\frac{\mathrm{c}T_r}{2}$, then $B_{\mathrm{IF}} \approx B_\tau \approx n\Delta f$. The DFT output can be explained from the perspective of PD processing. The range coupled frequency produced by the maximum target time shift of $\tau = \frac{1}{n \cdot \Delta f}$ covers a maximum frequency interval of $\frac{\Delta f}{T_r} \cdot \frac{1}{n \cdot \Delta f} = \frac{1}{nT_r}$. This covers only $\frac{1}{n}$ of the DFT's unambiguous Doppler frequency $\frac{1}{T_r}$, and still leaves a large frequency interval of the DFT output $(\frac{N-1}{N} \frac{1}{\Delta f})$ for velocity measurement. If signal processing methods can be adopted to minimize the measurement error of the range coupled frequency, the DFT output can be seen as a velocity or Doppler value in one PRF, for which there exists a maximum measurement error of $\frac{1}{nT_r}$. Thus an SF radar system with a range window of $\delta R = n\frac{\mathrm{c}T_r}{2}$ in the HPRF mode can be regarded as high range resolution PD radar without velocity ambiguity.

5 Ambiguities and their resolutions in HPRF PD SF radar

There exist two kinds of ambiguities in HPRF PD SF radar systems. One is range ambiguity with period PRT in the range window when $R_{\max} > \frac{\mathrm{c}T_r}{2}$. The other is high resolution ambiguity, i.e., the ambiguity of the high resolution range profile within $\frac{1}{\Delta f}$ after DFT processing of the SF echo.

5.1 Range ambiguity with period PRT and its resolution

In an HPRF mode there exists PRT range ambiguity for a target echo when $R_{\max} \gg \frac{cT_r}{2}$. Since the range window size is controlled by receiver bandwidth in the radar system, the remaining PRT ambiguity of the target echo after reception is reduced to n for a receiver bandwidth of $B_{\rm IF} = n\Delta f$. A phase difference (PHD) method can be used to resolve the remaining PRT ambiguity in the range window.

According to eq. (6), a target echo with a delay of p ($p < n$) PRT with reference to the oscillator starting time t_0 has a frequency element $p\Delta f$ after quadrature detection. This frequency element produces a phase difference of $\delta\phi$ between two closely spaced echoes

$$\delta\phi = 2\pi p\Delta f T_s. \tag{16}$$

As Δf and T_s are known parameters, the remaining ambiguity in p can be resolved if the phase difference $\delta\phi$ can be determined. To guarantee an unambiguous phase difference, $\delta\phi$ must satisfy the condition $\delta\phi < 2\pi$, i.e.,

$$p < \frac{1}{\Delta f T_s}. \tag{17}$$

Because the sampling interval of T_s usually satisfies $T_s \leqslant \frac{1}{B_{\rm IF}} \approx \frac{1}{n\Delta f} \leqslant \frac{1}{p\Delta f}$, eq. (17) is subsequently satisfied. Therefore the key to the PHD method is how to evaluate the phase difference $\delta\phi$. A solution which utilizes the DFT values of several nearby range cells for the same target to solve $\delta\phi$ has been proposed in ref. [6]. The performance of this method relies strongly on radar signal's SNR. After ambiguity resolution with this method, the target range can be restricted to within one PRT. Then together with the sample position information, the target delay precision can be located further within $\frac{1}{\Delta f}$.

5.2 High range resolution ambiguity and its resolution

After PRT ambiguity resolution with the PHD method, there still exists range ambiguity within $\frac{1}{\Delta f}$ for the target's HRRP due to the unknown target velocity. The waveform analysis in the frequency domain (WAIFD) is based on the relative DFT magnitudes of nearby range cells for the same target[6]. The WAIFD method estimates the waveform center within $\frac{1}{\Delta f}$ by interpolation and hence can measure target range precisely.

The range resolution of WAIFD method is equal to $\frac{c}{2N\Delta f}$, which is obtained from the frequency resolution of DFT processing. The ranging precision depends on the noise power and several other factors such as the specific waveform analysis method used and radar parameter setup.

6 Processing procedures of HPRF PD SF radar and computer simulation results

Based on the earlier analysis, SF radar may be viewed as a PD radar with an HRR capability, i.e., it has high range resolution and can obtain both high range resolution and velocity unambiguously in a HPRF mode. The difficulty, however, lies in the coupled frequency shift produced in the target range profile. If $B_{\rm IF} \approx B_\tau \approx n\Delta f$ can be assumed through system parameter design, then using the method mentioned above, high resolution ranging and unambiguous velocity measurement can be obtained within one burst. The processing procedure for HPRF PD SF radar is shown in Figure 3.

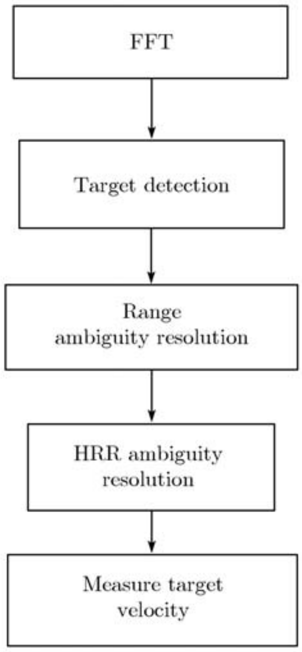

Figure 3 Processing procedure of HPRF PD SF radar.

In this section the above analysis is verified through computer simulation. The simulation results are presented in two parts: First, it is shown that HPRF PD SF radar can achieve both unambiguous velocity and HRR in one burst. Second, it is shown that HPRF PD SF radar can achieve high resolution ranging through ambiguity resolution.

6.1 Unambiguous velocity measurement and high range resolution of HPRF PD SF radar

6.1.1 With SF waveform HPRF PD radar has HRR ability. The radar parameters used in the simulation are as follows: operating frequency f_0=10 GHz, PRT=20 μs, transmit pulse duration τ=200 ns, frequency step Δf=0.5 MHz. The number of frequency steps in one burst N=256, the IF amplifier is Gaussian in the frequency domain with a 1.5 dB bandwidth of B_{IF}=5 MHz. The sampling frequency f_s=10 MHz. With these parameters, the unambiguous range is 3000 m, the unambiguous velocity is ±750 m/s, the range resolution is ΔR=1.1719 m and the velocity resolution is Δv=2.9297 m/s.

Consider two moving scatterers at ranges 11 m and 13 m both with a velocity of 300 m/s. Figure 4 shows the DFT output of both standard PD processing ($\Delta f = 0$) and the new PD SF processing.

From the simulation results, it is evident that the standard PD radar is unable to differentiate between two targets moving at the same velocity but located at different ranges. However, the PD SF approach is able to resolve the two targets quite clearly.

The corresponding FFT shifts of the range coupled frequency component relating to the two scatterers are theoretically 9.3867 and 11.0933 bins respectively. By comparing Figures 4(a) and 4(b), it is clear that the shifts of the two peaks are produced by the range coupled frequency shifts.

6.1.2 Processing effect for fluctuating target. Here consider a moving scatterer with a velocity of 300 m/s at ranges 11 m, whose amplitude fluctuates independently from pulse to pulse according to the following model:

$$A(1 + \sigma_0 n),$$

where A can be seen as a constant element of the target echo amplitude, whereas $A\sigma_0 n$ is a fluctuating element which fluctuates independently from pulse to pulse, where n conforms to normal distribution with a standard deviation of 1.

Let $A = 1$, $\sigma_0 = 1$. Figure 5 shows the DFT output of the SF PD processing.

Analysis shows that target fluctuation does not affect the resolution of the HPRF SF radar, and the DFT processing introduces N times of improvement for the target fluctuation, i.e., the fluctuating element of target only adds a noise base of $\frac{1}{N}\sigma_0$ deviation to the processing result.

6.2 PRT range ambiguity and high range resolution ambiguity in HPRF PD SF radar and their resolutions

6.2.1 PRT range ambiguity and its resolution

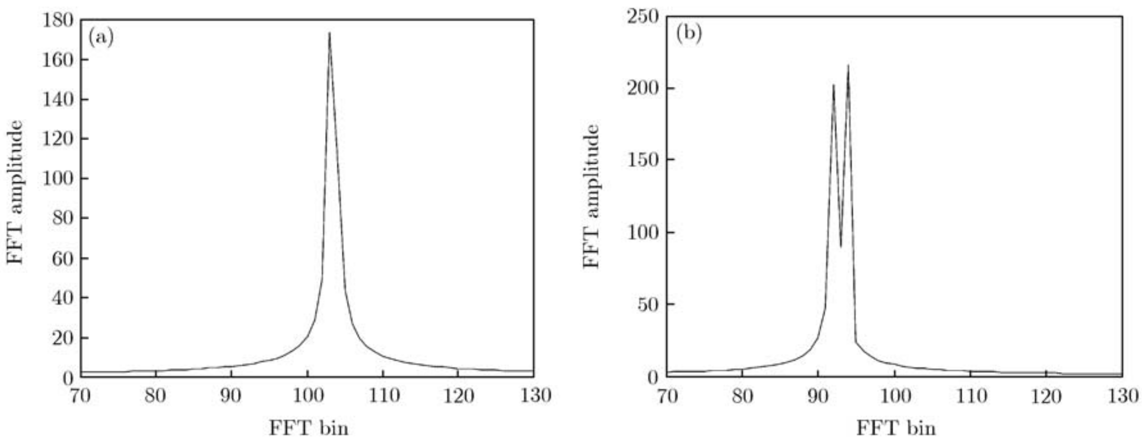

Figure 4 (a) Standard PD's FFT result(range resolution ΔR=30 m, v=300 m/s, corresponding spectrum peak at the 103rd FFT bin); (b) PD SF FFT results(range resolution ΔR=1.1719 m, v=300 m/s, corresponding spectrum peaks at the 92nd and 94th FFT bin).

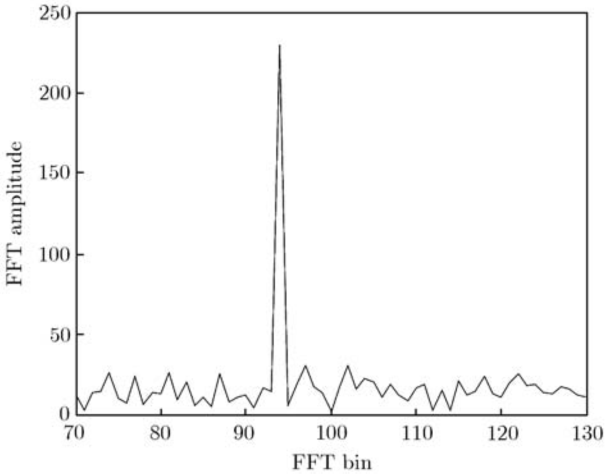

Figure 5 FFT output of a fluctuating target.

with PHD method. Here, the system parameters are the same as in subsection 6.1 with a receiver SNR of −10 dB. The target has an initial range of 7200 m (the corresponding PRT ambiguity is a factor of 2), and a velocity of 660 m/s. The processing procedure in the simulation software is as follows: First, the echo is generated from each range cell after mixing and second, every burst of N samples from each range cell is FFT transformed, detected and threshold. For the detected targets, the two range cells of largest amplitude are selected and then the phase difference of the FFT bin corresponding to the two targets is computed to get the ambiguity. The computation method is described in section 5.

Figure 6(a) shows the FFT output of multiple samples when the target moves to range 7196.6 m, in which the largest echo amplitude occurs at the 13th range cell and 226th FFT bin. Figure 6(b) shows the phase difference between samples 12 and 13. The phase difference between samples 12 and 13 in FFT bin 226 is 0.5690 radians which corresponds to a range ambiguity factor of 2 when compared with the theoretical phase difference of $2\pi\Delta f T_s = 0.3142$ for two adjacent samples for a target with an ambiguity factor of 1. This simulation result proves that the principle of PHD method is feasible for PRT ambiguity resolution.

To test the performance of PHD method we let the received SNR vary linearly between −28 and −10 dB at a step of 2 dB. For each SNR value, the simulation system transmits 30 bursts of SF pulses and for each burst 40 Monte-Carlo simulations are run. After simulation, the error probability of the ambiguity resolution is computed, where the error probability is defined as the total resolution errors over all the simulations. The simulation results are shown in Figures 7 and 8.

Figure 7 shows the error probability of the PHD method as a function of SNR. Figure 8 shows the error probability of the PHD method as a function of coarse range cell. Figure 7 shows that the performance of the PHD method is a function of system noise and improves with increasing SNR. Figure 8 shows that the error probability of the PHD method varies periodically as a target moves across different coarse range cells, proving that the initial sampling position affects the performance

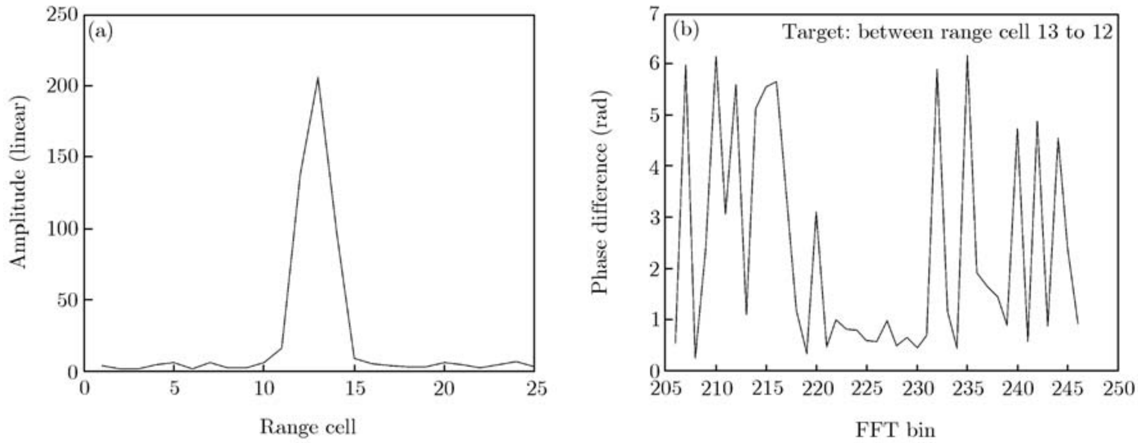

Figure 6 (a) FFT output of multiple samples at the target bin; (b) phase difference of FFT output at the target bin between two nearby samples.

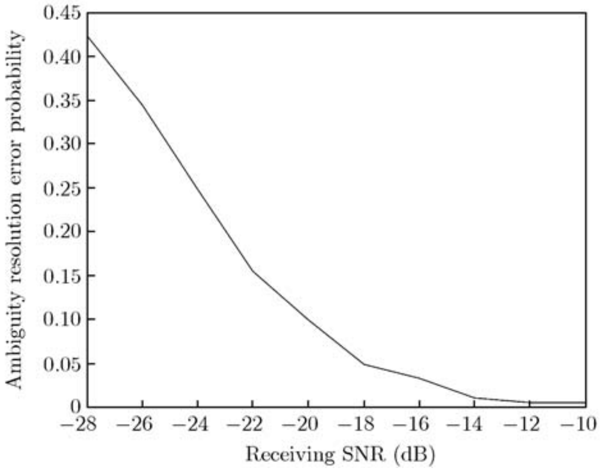

Figure 7 Performance of the PHD method depends on SNR.

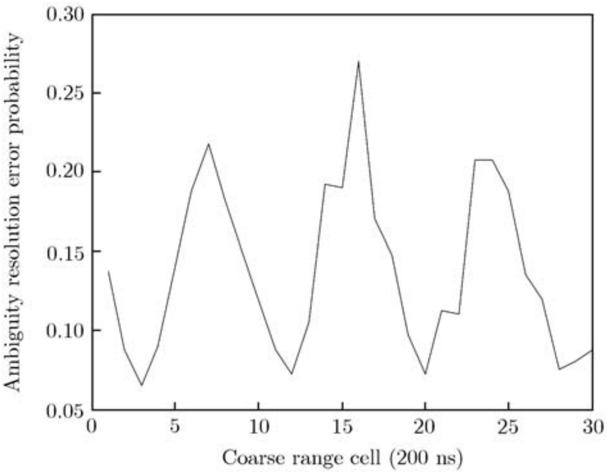

Figure 8 Performance of the PHD method depends on the initial sampling position.

of PHD method. For tracking radar, improved performance can be expected with additional data processing after ambiguity resolution of the other bursts.

6.2.2 High range resolution ambiguity and its resolution with waveform analysis method in frequency domain. Here, the system parameters are the same as in subsection 6.1.1 and the PRT ambiguity resolution result is assumed to be valid. The processing procedure in the simulation software is as follows: First, the echo is generated from each range cell after mixing and second, every burst of N samples from each range cell is FFT transformed and then threshold detected. For detected targets, the WAIFD method is employed to obtain the waveform center and then the HRR range and the velocity value. The waveform analysis method adopted is waveform area analysis method[9]. The simulation computes the range/velocity range precision variation as a function of SNR for the maximum range/velocity error and the minimum range/velocity error. Averaging over all the Monte-Carlo simulations for a given range cell, a standard deviation of range/velocity is computed and for all the range cells at a particular SNR a range/velocity range variation error is computed.

Consider a target with an initial range of 1200 m and a velocity of 660 m/s. The receiving SNR varies linearly between −28 and −10 dB with a step of 2 dB. For each SNR, the simulation system transmits 30 bursts of SF pulses, and for each burst 40 Monte-Carlo simulations are carried out. The simulation results are shown in the following Figures 9–13.

Figures 9–13 shows how the performance of the WAIFD method depends on SNR. Figures 9 and 12 are the range/velocity range error variation. Figures 11 and 13 are the range/velocity range error standard deviation. Figure 10 shows the pulse duration divided by the ranging error range variation. During simulations, for each coarse range cell there is a range/velocity value as a result of each Monte Carlo simulation. The range/velocity range error variation under each SNR is computed according to the maximum and minimum value of 40 Monte-Carlo simulation results over all coarse range cells. Besides, based on 40 Monte-Carlo simulation values for each coarse range cell, a range/velocity standard deviation error can be obtained from the results of all the coarse range cells. The range/velocity standard deviation range error can be computed at each SNR.

The simulation results show that the WAIFD method has the capability for high resolution, and the ranging precision is related to system's noise power, improving with SNR. For the simulation system parameters used, the ranging precision of the WAIFD method has an improvement of between 2 to 17 times for SNRs varying between −28 dB and −10 dB. The velocity measurement precision is related to the ranging precision, and varies from 5 m/s to 41 m/s for SNR values between −28 dB and −10 dB.

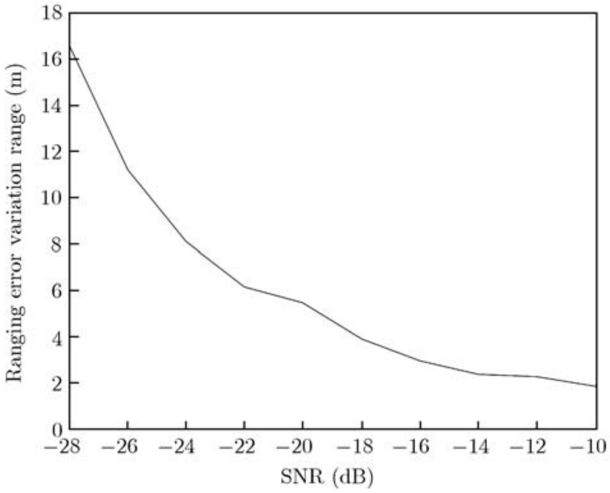

Figure 9 Ranging error variation range with SNR.

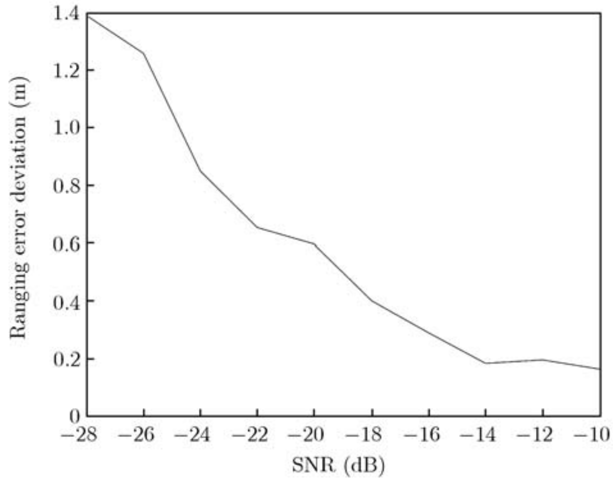

Figure 11 Ranging error standard deviation range with SNR.

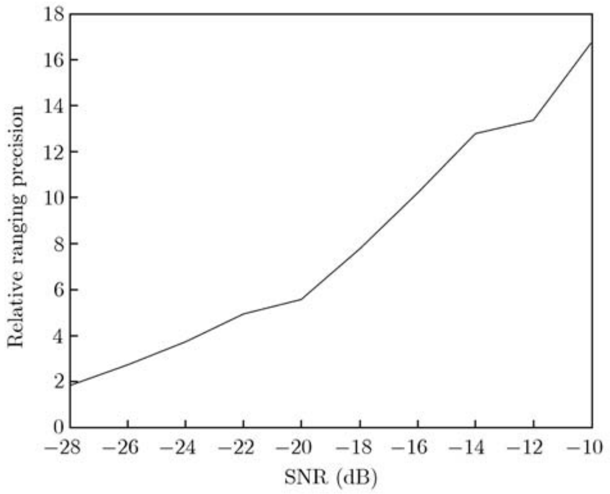

Figure 10 Pulse duration over ranging error variation range with SNR.

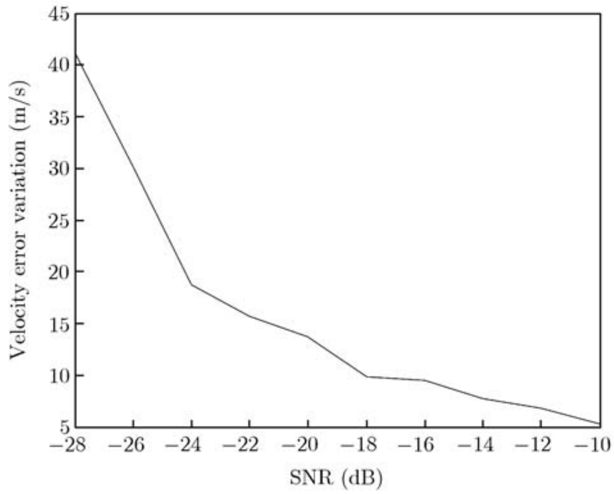

Figure 12 Velocity error variation range with SNR.

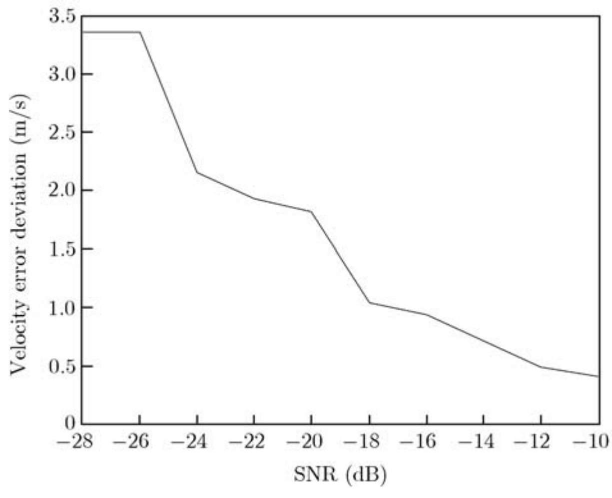

Figure 13 Velocity error standard variation range with SNR.

7 Summary

This paper introduces a PD SF radar scheme which can simultaneously obtain high range resolution and unambiguous velocity measurement under HPRF operation. The radar scheme has been analyzed and solutions are given for resolving key problems such as parameter design, signal processing, as well as ambiguity resolution. Analysis and simulation results show that this method has both the advantage of PD radar and SF radar. It can measure a target's unambiguous velocity and obtain target HRRF in a single dwell and is therefore highly applicable to many new radars.

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