Method to Improve Range and Velocity Error Using De-interleaving and Frequency Interpolation for Automotive FMCW Radars

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Abstract

In the paper, we propose method to obtain the range and velocity with improved error depending on each distance (long, middle, and short) of the target for the automotive Frequency Modulation Continuous Wave (FMCW) radars. While target is in the long distance, the range and velocity are roughly extracted, for near-range target with the high collision probability, the de-interleaved method in the time domain and frequency interpolation in the frequency domain are applied to obtain more accurate range and velocity.

Keywords: *Automotive FMCW Radars, Frequency Interpolation, Velocity Error*

1. Introduction

77GHz radars are already on the market as the active safety system to protect the driver and minimize damage of all road vehicles. The radar sensor systems are one of important elements in automotive technology, because these are virtually unaffected by harsh environmental conditions such as weather and light quality. The 77GHz FMCW radars are especially effective and presently on the market as the safety systems for high performance automotive applications [1][2][3].

In FMCW radar, a typical approach to extract range and velocity is to analyze the Fourier spectrum of the received beat signal. The Fourier spectrum is usually determined by digital method using the beat signal sampled by ADC (Analog Digital Converter).

However, since accurate beat frequency measurement can be possible only up to frequency step determined by ADC sampling rate, the number of sampling, and chirp period, the step size of estimated range and velocity is limited.

In this paper, the main idea of the proposed method is to obtain range and velocity with different error depending on the distance (long, middle, or short) of the target from the radar. The basic concept was introduced in the previous paper [4]. While the range and velocity extracted using only FFT for targets in the long distance, more accurate range and velocity can be obtained by de-interleaving method and frequency interpolation for objects in the middle and short range zone.

Section I provides the FMCW radar principle. In section II, the proposed adaptive range profile algorithm will be described in details.

2. Overview of FMCW Radar

FMCW radar transmits a frequency-modulated continuous wave to measure the range and velocity of the target. Figure 1 shows frequencies as a function of time in the transmitted signal and received signals for a stationary target [5][6]. Here, f_c is the center frequency, B is the modulation bandwidth, and f_0 is the starting frequency, and t_d is the delay time between transmitted and received signals. T is a chirp period which is one half of PRI(Pulse Repetition Interval).

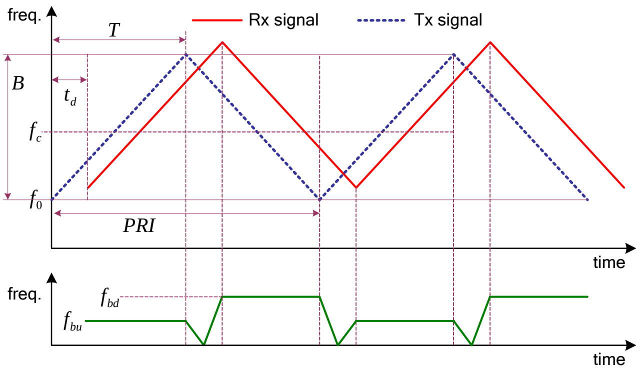

Figure 1. Transmitted, received, and beat frequencies as a function of time for a moving target

When the target is not stationary the received signal will contain a Doppler shift term in addition to the frequency shift due to the time delay t_d. The beat frequency is difference between the transmitted signal and received signal and the beat frequencies for the up chirp and down chirp are denoted as respectively as f_{bu} and f_{bd}. The range beat frequency f_r and the Doppler frequency f_d are mathematically expressed as $f_r = |f_{bu} + f_{bd}|/2$ and $f_d = |f_{bu} - f_{bd}|/2$.

The range beat frequency f_r and Doppler frequency f_d can be obtained by signal processing, and then the distance and velocity of the target can be estimated as Equation (1) and (2).

$$R = \frac{cTf_r}{2B} \tag{1}$$

$$V = \frac{cf_d}{2f_c} \tag{2}$$

In a FMCW radar, the ideal unambiguous range is $cT/2$. In practice, however, the maximum range is normally selected as fewer than 10% of the unambiguous range [6]. Depending on the applications, the maximum range and velocity are selected and then, the corresponding ranging beat frequency $f_{b\max}$ and Doppler $f_{d\max}$ are calculated. Therefore, the required sampling rate of ADC should be $f_s \geq 2(f_{r\max} + f_{d\max})$.

Typically, the range spectrum of the beat signal sampled with frequency f_s is computed with N_s point DFT(Discrete Fourier Transform) for every chirp periods, using the FFT(Fast Fourier Transform) algorithms[7] as shown in Figure 2. Here, Δf is frequency step and N_s is the number of data sampled over chirp period T.

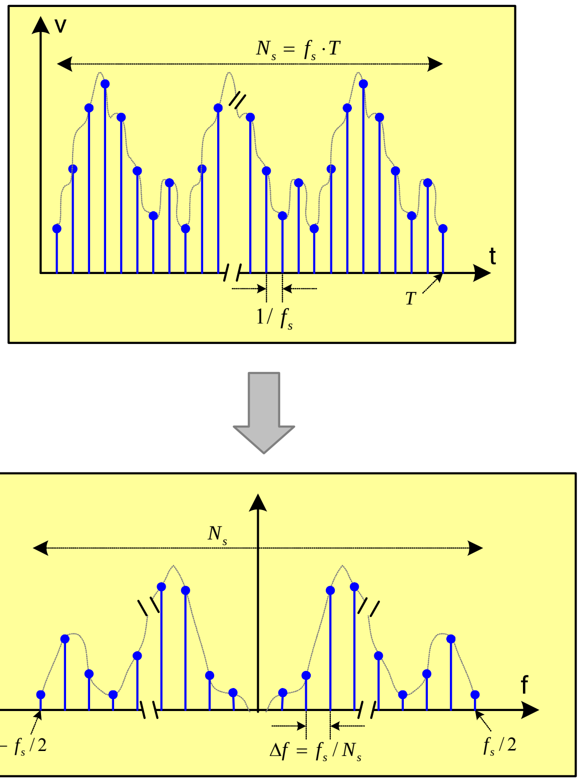

Figure 2. Data sample of beat signal and discrete frequency spectrum

The measured beat frequency error is expressed as difference between the ideal beat frequency in the continuous frequency domain and the beat frequency in the discrete frequency domain in Equation (3). Here, f_b^{ideal} is ideal beat frequency, f_b^{FFT} is discrete beat frequency by FFT, and f_{err} is the beat frequency error. The maximum error of beat frequency is equal to $\Delta f = f_s / N_s$.

$$f_{error} = f_b^{ideal} - f_b^{FFT} \tag{3}$$

Thus, the range step size and velocity step size are equal to Equation (4) and (5), respectively. The maximum range error and velocity error also are equal to ΔR and ΔV, respectively. If we can choose longer chirp period, the velocity step size can be more diminished but the range step size is not changed because frequency step size Δf is fixed as $1/T$.

This limitation can be, however, overcomed using more data sampled by multiple modulation periods at the same sampling rate[7]. If, for example, two chirp periods are used, then $2N_s$ data may be sampled and frequency step $\Delta f / 2$ may be obtained. The limitation of range and velocity may be resolved with a proper choice of sample length.

$$\Delta R = \frac{cT\Delta f}{2B} = \frac{cT}{2B} \cdot \frac{f_s}{N_s} \tag{4}$$

$$\Delta V = \frac{c\Delta f}{2f_c} = \frac{c}{2f_c} \cdot \frac{f_s}{N_s} \tag{5}$$

3. The proposed method

In Figure 3, Car #0 has a FMCW radar with a maximum range $R_{\max}$. We assume that Car #1 and Car #2 are moving in *middle range zone* and *long range zone* on the same road lane, respectively. In this scenario, while Car #0 can roughly detect the distance from Car #2, the range from Car #1 should be more accurately extracted because Car #2 has a higher probability of collision. We also assume that Car #1 is moving into *short range zone*. In the case, more accurate range and velocity should be obtained.

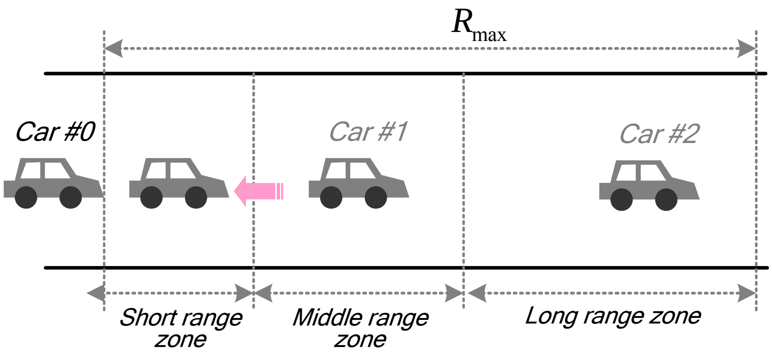

Figure 3. Scenario example to explain the proposed method

If the maximum range is reduced by one half of $R_{\max}$, the corresponding maximum beat frequency and required sampling rate can be shortened by half. However, since the number of data sampled in one chirp period is also one half of N_s, the maximum range error and velocity error are not changed by Equation (4) and (5).

As above mentioned, finer range and velocity step size may be resolved using samples over several chirp periods for FFT. However, this method leads to a high computational complexity by increasing the number of data.

In the paper, we proposed method to improve range and velocity error as the distance (long, middle, or short) of the target by using de-interleaving method and frequency interpolation as shown in Figure 4.

In the example of Figure 3, for obtaining range and velocity of Car #2 in the long distance, we use FFT with N_s samples. Then, the maximum range error and velocity error are equal to Equation (4) and (5). This is referred to as *long-range detection*.

If target(Car #1) is located in the middle range zone, the maximum range to be detected and the corresponding maximum beat frequency in a FMCW radar are reduced by half. Moreover, required ADC sampling rate can be reduced by half.

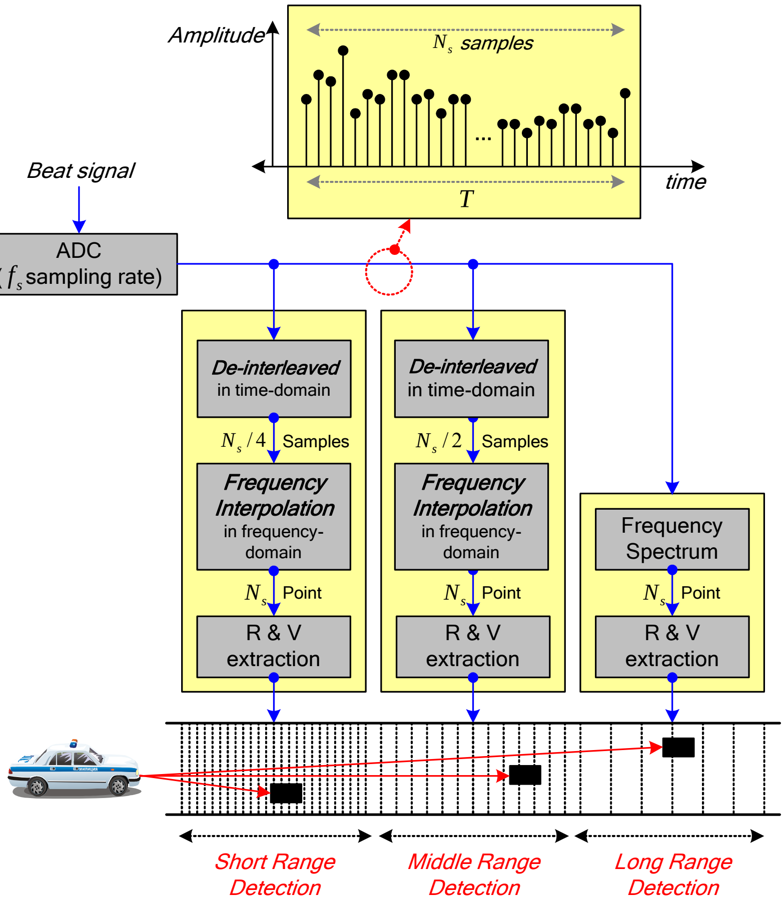

Figure 4. The concept of signal processing in the propose method

In a general radar system, however, the ADC sampling rate depends on the requirements of the applications and initial sampling frequency cannot be changed because of the hardware constraints of system implementation.

For reducing the number of samples, we employ de-interleaving method in the time domain without changing ADC sampling rate. Figure 5 shows that data samples of example of Figure 2 are down-sampled into $N_s/2$ by de-interleaving method in order to adjust the maximum range to meet the *middle-range detection*. However, if $N_s/2$ data are processed using FFT, the range step size and velocity step size are not changed because the required ADC sampling rate becomes also one half of f_s by de-interleaving method.

In the paper, for overcoming the limitation, we use the frequency interpolation using zero padding FFT in the frequency domain. Zero padding is useful when the frequency sampling is considered to be too sparse to provide a good representation of the continuous-frequency estimation spectrum[8]. In *middle-range detection* of Figure 5, zero padding FFT with N_s point is used to obtain fine range and velocity with $0.5\Delta R$ and $0.5\Delta V$ in comparison as *the long-range detection*.

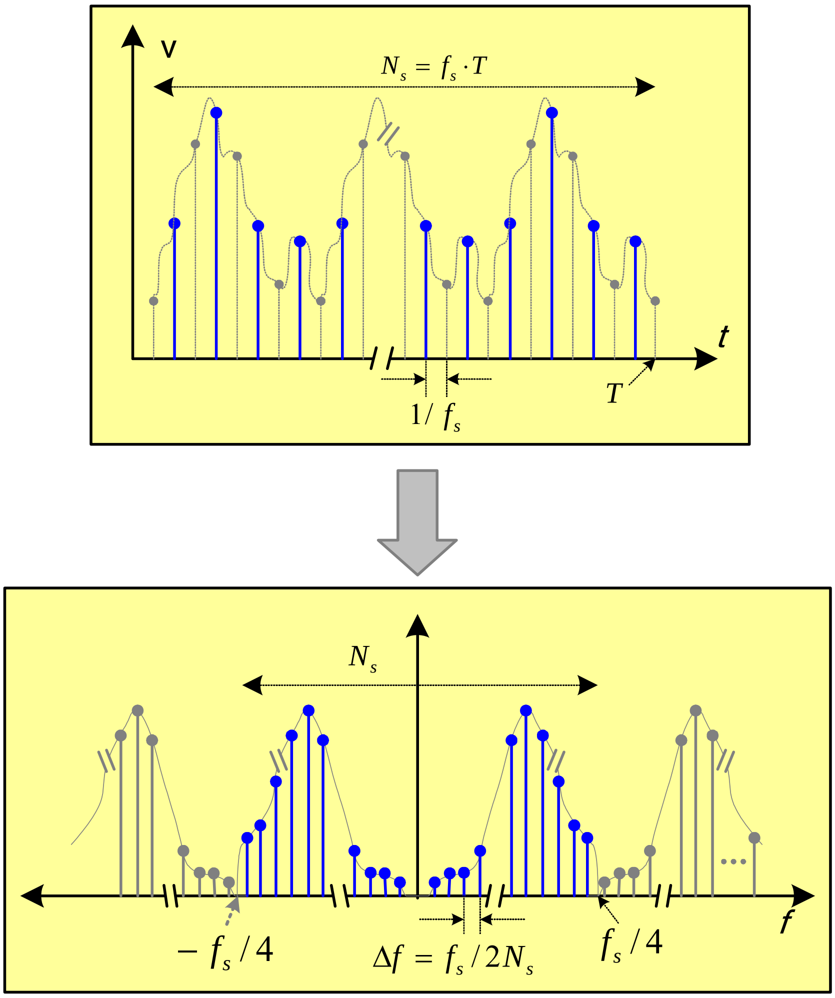

Figure 5. Example of middle range detection in the proposed method

Lastly, when the target distance from radar is very near in *short range zone*, we must extract an accurate range and velocity. Using the same method, we can reduce sampling rate and the number of sample, and then we can obtain the accurate range and velocity by the frequency interpolation. This is referred to as *short-range detection*.

4. Simulation Results

We simulate this algorithm using *Matlab*. The detail properties of FMCW radar, such as the transmitted bandwidth, the carrier frequency, the chirp period, the PRI(Pulse Repetition Interval), and the modulation frequency, are shown in Table 1. The sampling frequency of ADC is 2 MHz because the maximum range is 200 m and the maximum beat frequency is 533 kHz.

The simulation result of *long*-, *middle*- and *short-range detection* is shown in Table 2.

For *long-range detection*, all 1000 data sampled during a chirp period are applied with 1024 point FFT to detect range up to maximum range 200 m.

In *middle- detection*, the 1000 samples are de-interleaved into 500 in the time domain to obtain maximum range up to 100m and these down-sampled data are computed by 1024 point FFT with zero padding.

For *short-range detection*, de-interleaved 250 samples in the time domain for maximum distance 50m, are processed with Fourier spectrum interpolation in the frequency domain.

Table 1. The properties of FMCW radar

Item	Nomenclature	Specification
Bandwidth	B	200MHz
Carrier frequency	f_c	76.5GHz
Chirp period	T	0.5ms
PRI	T_m	1ms
Modulation frequency	f_m	1kHz
ADC sampling rate	f_s	2MHz

We can know that the maximum range error and velocity error of *short-range detection* are decreased in comparison with them of the *long-range detection*.

Table 2. The simulation result of long range and middle-range detection

Type	*Long-range detection*	*Middle-range detection*	*Long-range detection*
The maximum range	200m	100m	50m
Number of samples de-interleaved in the time domain	1000	500	250
FFT point	1024	1024	1024
Frequency step size	1.95kHz	0.98kHz	0.49kHz
Maximum range error	0.73m	0.36m	0.18m
Maximum velocity error	13.8km/h	6.9km/h	3.4km/h

Figure 6 shows the simulation results of *long*-, *middle*-, and *short-range detection* for stationary target. The target range is 30m~50m. X-axis is target's distance and y-axis is error of detected range. We can know range error of the *short-range detection* is lowest.

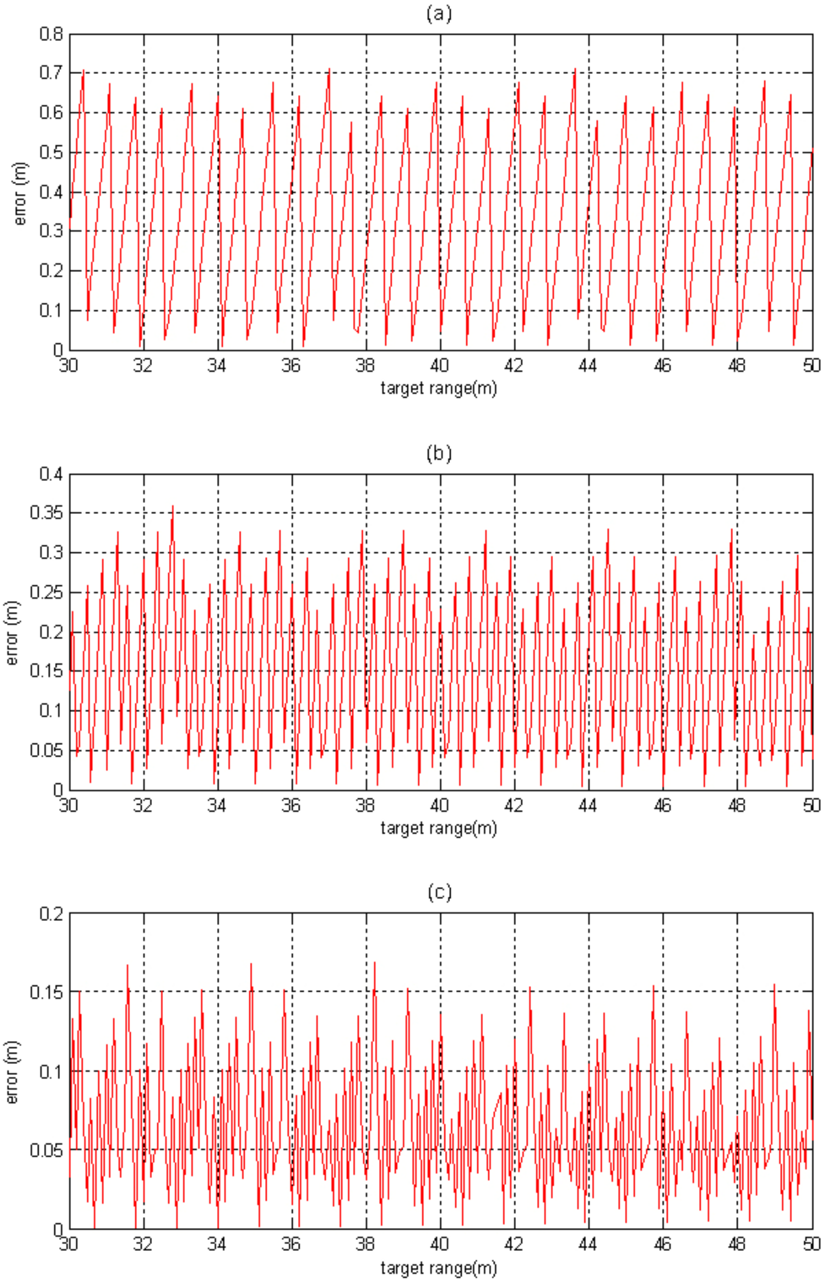

Figure 6. The error of extracted range when stationary target in is 60m~90m (a) by long-range detection (b) by middle- range detection (b) by short range detection

Figure 7 shows the simulation results of *long*-, *middle*-, and *short-range detection* for moving target. The range of moving target is 50m and the velocity is -100km/h ~ 100km/h. X-axis is target's velocity and y-axis is error of detected velocity. We can also know velocity error of the *short-range detection* is lowest.

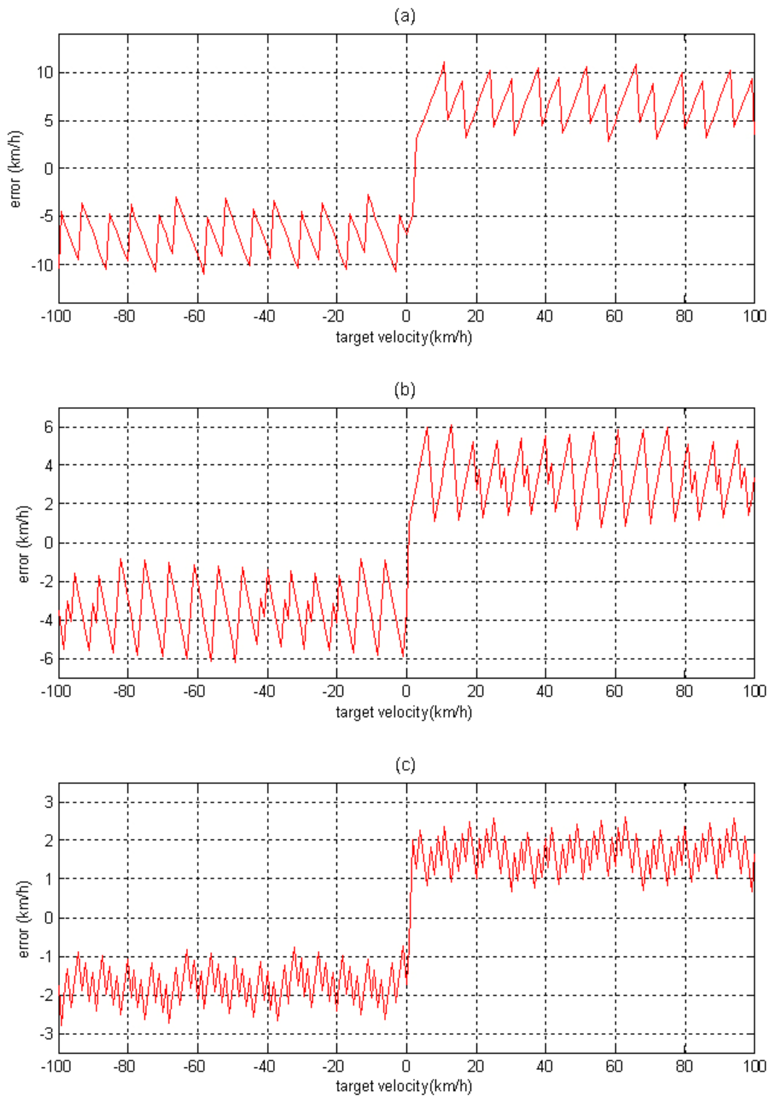

Figure 7. The error of extracted velocity when moving target's range is 50m and it's velocity is -100km/h~100km/h (a) by *long-range detection* (b) by *middle-range detection* (b) by *short range detection*

Next, we simulate the range profiles with multi-target. We assume that the distance of the ranges of targets are 49.0m, 48.3m, 36.4m, 35.7m, and 35.0m. Figures 8 shows the FFT results of *long*-, *middle*-, and *short-range detection* for these five targets. X-axis is range of target and y-axis is normalized PSD(Power spectrum density).

While we cannot detect the exact range of the targets by *long*- and *middle-range detection*, *short-range detection* can provide fine range profiles. That is, in *short-range detection*, all ranges of five targets are extracted as 49.12m, 48.2m, 36.66m, 35.74m, and 34.82m, while only two targets (49.12m and 36.66m) can be seen by *long-range detection*.

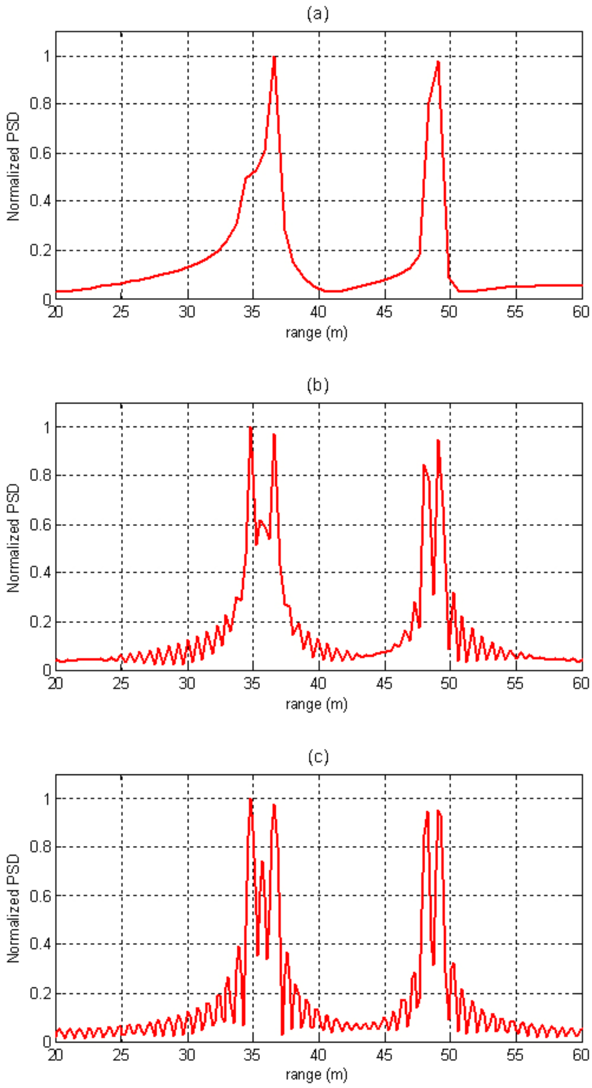

Figure 8. Normalized range profile extracted (a) by *long-range detection* (b) by *middle range detection* (c) by *short range detection*

5. Conclusion

We proposed method to improve the range and velocity error as each range (long, middle, and short) of the target for the automotive FMCW radar. For the target in the long distance, the range is extracted with the coarse range and velocity using only FFT. For *middle*- and *short- range detection*, the sampled data of beat signal is de-interleaved in the time domain to adjust maximum beat frequency to be detected, and then frequency interpolation by zero padding FFT in the frequency domain is used to obtain more accurate range and velocity.

Acknowledgements

This work is supported by the basic research program of the Ministry of Education & Science Technology.

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