

Moving Target Detection Algorithm for Millimeter Wave Radar Based on Keystone-2DFFT

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Abstract: Millimeter wave radar has the advantage of all-day and all-weather capability for detection, speed measurement. It plays an important role in urban traffic flow monitoring and traffic safety monitoring. The conventional 2-dimensional Fast Fourier Transform (2DFFT) algorithm is performed target detection in the range-Doppler domain. However, the target motion will induce the range walk phenomenon, which leads to a decrease in the target energy and the performance of the target detection and speed measurement. To solve the above problems, this paper proposes a moving vehicle detection algorithm based on Keystone-2DFFT for a traffic scene. Firstly, this paper constructs and analyzes the Frequency Modulated Continuous Wave (FMCW) moving target signal model under traffic monitoring scenario's radar observation geometry. The traditional 2DFFT moving target detection algorithm is briefly introduced. Then, based on mentioned signal model, an improved moving vehicle detection algorithm based on Keystone-2DFFT transform is proposed. The method first input the echo, then the range walk is removed by keystone transformation. the keystone transformation is achieved via Sinc interpolation. Next is transform data into range-Doppler domain to perform detection and speed estimation. The algorithm is verified by simulation data and real data.



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Keywords: millimeter wave radar; traffic monitoring; keystone transformation; 2DFFT transform; range walk

1. Introduction

The millimeter wave radar is an active sensing sensor with the advantages of all-day and all-weather capability [1], and can penetrate clouds, rain, fog, and smoke to monitor surrounding targets with high precision. Compared with other microwave bands, millimeter wave radar has better Doppler and range resolution performance [2]. Therefore, it is widely used in intelligent transportation systems, unmanned driving, and other fields [3–5]. The representative frequency band is 77 GHz. In the intelligent transportation system, 77 GHz millimeter wave radar can realize target speed measurement, ranging, and angle measurement [6]. Except for intelligent transportation applications, the 77 GHz millimeter wave radar can also be used in traffic monitoring to ensure traffic safety.

The 2-dimensional FFT (2DFFT) is a widely used algorithm to detect a moving target and estimate its radial speed in Frequency-Modulated Continuous Wave (FMCW) radar. It gathers the pulses with multiple repetitions to form the 2D radar data. Then, it applies 2DFFT to transform it into range-Doppler domain to get the point liked moving target signature. However, because it needs multiple pulses, the moving target may cross the range cell due to its motion. This phenomenon is referred to as range migration, which is composed of range walk and range curvature [7–12]. Range walk will cause defocusing and displacing effects on moving targets, which makes detection difficult [13–18]. As will be shown in this paper, the range walk is the key factor in detection performance degradation.

If the traditional 2DFFT detection algorithm is directly used, those moving vehicles with range walk will lead to the defocusing and reducing energy. Eventually, some targets might not be detected accurately. In such cases, the traditional 2DFFT detection algorithm is no longer applicable. Hence, it is necessary to remove the range walk to ensure the effectiveness of moving target detection [19–21].

The keystone transformation is an effective algorithm for correcting target range migration. In 1998, the keystone transformation was proposed by Perry [22], which is applied to the Synthetic Aperture Radar (SAR) to achieve moving target focusing. In 2005, Shunsheng Zhang et al. introduce the keystone transformation to Pulsed Doppler radar to realize the accumulation and detection of weak target signals [23–28]. The algorithm can accurately remove the range migration of moving targets without knowing the target motion parameters. The First-Order Keystone transformation is proposed by Perry [22], and is used to remove the target range walk. The Second-Order Keystone transformation is later proposed to remove the target range curvature in [29]. The above studies are mostly in the pulsed radar mode; the FMCW radar signal is dechirped in fast time domain, which is different from the pulsed radar signal model. Hence, the traditional keystone is not applicable in FMCW radar condition. The above situation makes researchers reconsider and analyze traffic moving target detections with FMCW radar.

To solve the above problems, this paper establishes and analyzes a new moving target detection algorithm entitled Keystone-2DFFT for FMCW traffic monitoring radar is proposed. Firstly, the FMCW radar moving target signal model is established for traffic monitoring scenarios, and the phenomenon of range walk and range curvature is analyzed. The analysis shows that the range walk is dominant effect in moving target signal model. Then, the keystone transformation algorithm is improved to adapt FMCW radar signal model. Next, the proposed Keystone-2DFFT is introduced in detail. The method first inputs the echo, then the range walk is removed by keystone transformation. The keystone transformation is achieved via Sinc interpolation. Next, transform data into range-Doppler domain to perform detection and speed estimation. The effectiveness of the algorithm is verified by the simulation and experimental data.

The rest of the paper is organized as follows: Section 2 introduces the simulation and experimental data. Section 3 establishes and analyzes the moving target signal model of FMCW radar. Section 4 introduces the traditional 2DFFT moving target detection algorithm and the proposed keystone-2DFFT algorithm for traffic scene. Section 5 is simulation and read data experiment. The TI's 77 GHz FMCW traffic monitoring radar is used to collect the real data. The last part is the conclusion.

2. Introduction of Simulation and Real Data

2.1. Simulation Data Experiment's Setup

The parameters of the simulation data are based on the AWR1243 radar development board from Texas Instruments, and they are shown in Table 1. The radar position is fixed, and operating at 77 GHz with a 346 MHz signal bandwidth. The signal Pulse Repetition Frequency (PRF) is 18,750 Hz, the number of pulses is 2048, and the number of range sampling points is 256.

Table 1. Simulation data parameters.

Parameter	Value
Center frequency	77 GHz
PRF	18,750 Hz
Signal bandwidth	346 MHz
Pulse number	2048
Range sampling points	256

Table 2 shows the parameters of the moving targets in the experiment. We simulated a stationary 80 target S1 and a moving target T1 for comparison. The range speed of the point target T1 was 15 m/s and the azimuth speed was 0 m/s.

Table 2. Target parameters.

Target	V_r (m/s)	V_a (m/s)
S1	0	0
T1	15	0

2.2. Real Data Experiment Setup

To verify the accuracy of the proposed method for vehicle detection in road traffic scenes, the 77 GHz FMCW traffic monitoring radar system is used to collect real data. The system consists of two devices: the Texas Instruments AWR1243 radar development board and the DCA1000 real-time data capture adapter. The DCA1000 is connected to the AWR1243 radar development board to stream out the raw complexed echo data. The traffic scene and radar setup are shown in Figure 1. The radar system is fixed on the center of bridge to detect vehicles on the both sides of road. The targets are moving towards or moving away from the radar. Hence, they usually have larger radial speed.

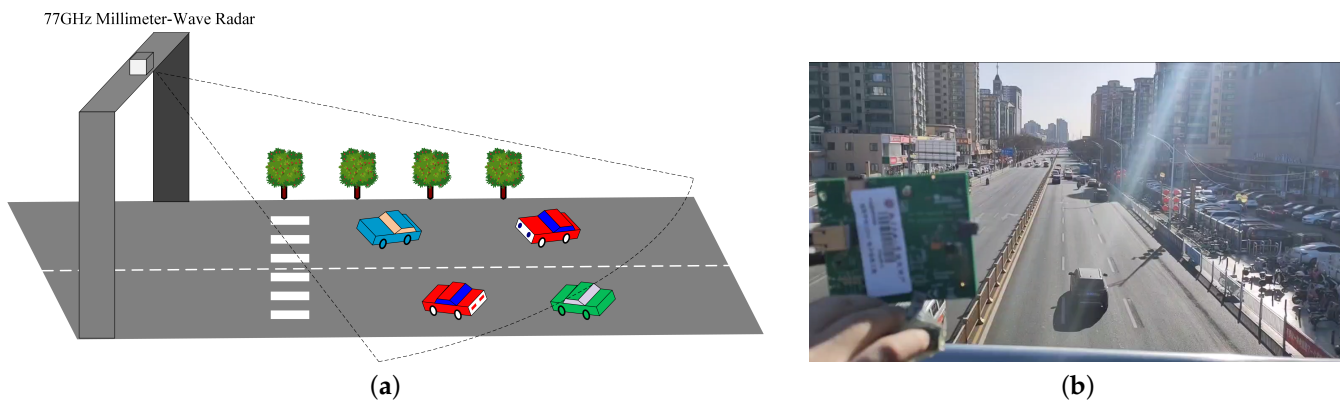


Figure 1. (a) Traffic scenario. (b) Radar field test scene.

The 77 GHz FMCW traffic monitoring radar system parameters for real data experiment are shown in Table 3, which is close to the simulation data parameters.

Table 3. Real data parameters.

Parameter	Value
Center frequency	77 GHz
PRF	19,230.77 Hz
CPI	0.162 s
Signal bandwidth	346 MHz
Frequency modulation rate	15.015 MHz/us
Pulse number	2688
Range sampling points	256

3. Moving Target Signal Model

3.1. Traffic Scene Geometry and Moving Target Signal Model

Figure 2a shows the geometry of the FMCW traffic monitoring radar, Figure 2b shows its top view. The radar is located at $(0, 0, H)$, the Y-axis is azimuth, the X-axis is range. The moving target is located at $M(x_0, y_0)$ with range speed v_r when the azimuth time $t_a = 0$. When FMCW traffic monitoring radar detects vehicles in complex road traffic scenarios, the radar position is fixed [30,31] and transmits the signal repeatedly. R_0 is the nearest range

from the target to the radar at zero time; after time t , the moving target is located at M' , and $R(t)$ is the instantaneous slant range between the moving target and the radar at time t .

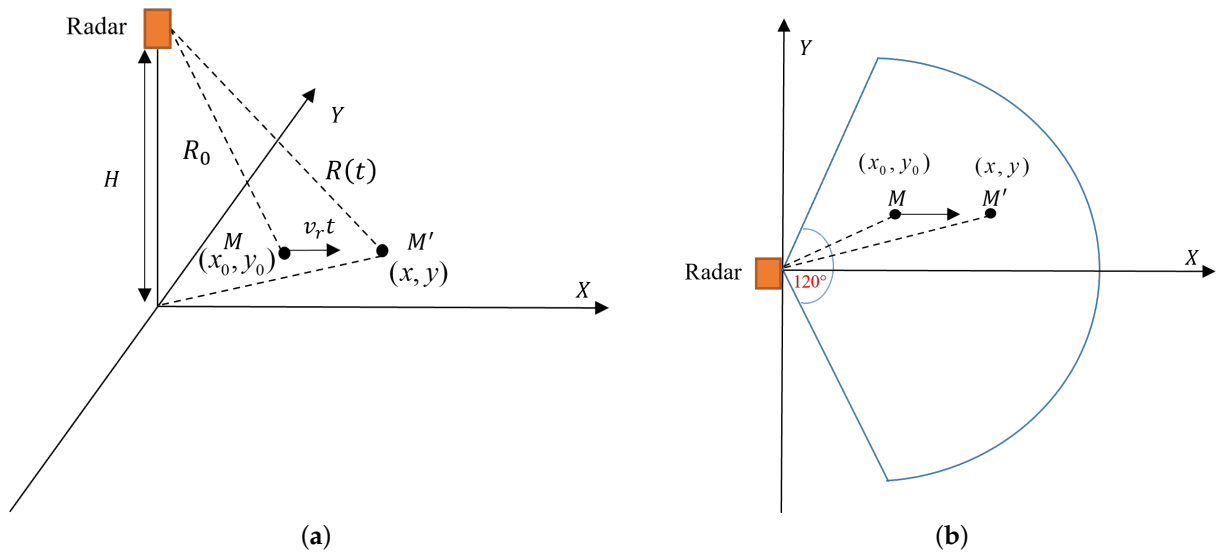


Figure 2. (a) 3D Geometry of FMCW radar moving target detection. (b) Top view of (a).

The range equation is expressed as:

$$R(t) = \sqrt{(H)^2 + (x_0 + v_r t)^2 + y_0^2} \quad (1)$$

It is typically to apply the Taylor formula expansion to the signal, which is shown as:

$$R(t) = R(t_0) + \frac{R'(t_0)}{1!}(t - t_0) + \frac{R''(t_0)}{2!}(t - t_0)^2 + \dots + \frac{R^{(n)}(t_0)}{n!}(t - t_0)^n \quad (2)$$

In Equation (2), when the range equation is expanded by the second-order Taylor series at the $t = 0$, other higher-order terms are ignored, and the result is given as:

$$R(t) \approx R(0) + \frac{R'(0)}{1!}(t - 0) + \frac{R''(0)}{2!}(t - 0)^2 = R_0 + \frac{x_0 v_r}{R_0} t + \frac{(R_0^2 - x_0^2) v_r^2}{R_0^3} t^2$$

$$\begin{cases} R(0) = R_0 \\ R'(0) = \frac{x_0 v_r}{R_0} \\ R''(0) = \frac{(R_0^2 - x_0^2) v_r^2}{R_0^3} \end{cases} \quad (3)$$

In Equation (3), t is given as $t = t_r + t_a$, where t_a is the azimuth slow time and t_r is the range fast time. This is because the FMCW radar transmits the signal continuously. Moreover, the target motion during in sweep period can not be ignored, so the range equation is related to the range fast time [32]. Substituting $t = t_r + t_a$ into Equation (3), we can obtain:

$$R(t) = R_0 + \frac{x_0 v_r}{R_0} (t_r + t_a) + \frac{(R_0^2 - x_0^2) v_r^2}{R_0^3} (t_a^2 + 2t_a t_r) \quad (4)$$

The radar transmits a complex exponential linearly chirped signal, which is:

$$s(t_r, t_a) = A \exp[j2\pi(f_c t + \frac{K_r t^2}{2})] \quad (5)$$

In the above formula, f_c is the center frequency, A represents the complex constant and window functions in both azimuth and range, which will be neglected in paper's following deduction. $K_r = B/T$ is the range frequency modulation slope, B is the signal bandwidth, and T is the pulse width. The block diagram of the radar system is shown in Figure 3. The FMCW millimeter wave radar transmits a linear frequency modulation signal and apply the dechirp processing to the returned echo signal [33].

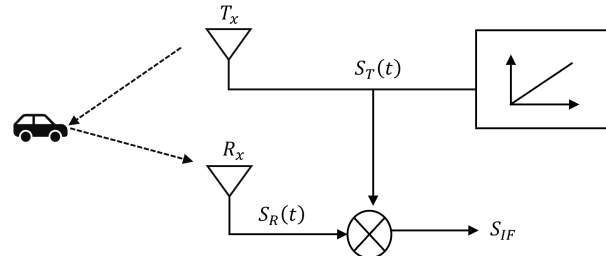


Figure 3. Block diagram of FMCW radar.

In Figure 3, the radar system transmits signal $S_T(t)$ from the transmitting antenna T_x . When the signal hits the target, the radar echo is transmitted back to the radar receiver antenna, and the received signal is $S_R(t)$. After dechirp processing, the expression of the dechirped signal $S_{IF}(t)$ is expressed as:

$$S_{IF} = A \exp[j2\pi(f_0(\tau - \tau_{ref}) + K_r(\tau - \tau_{ref})(t_r - \tau_{ref}) - \frac{K_r}{2}(\tau - \tau_{ref})^2)] \begin{cases} \tau = \frac{2R(t_r, t_a)}{c} \\ \tau_{ref} = \frac{2R_{ref}}{c} \end{cases} \quad (6)$$

In Formula (6), τ is the target echo delay and R_{ref} is the reference range. In the dechirp processing, range compression is by using the delayed signal to mix with the transmitted signal. The delayed time can be interpreted as the reference range; it is typically the center of the scene. By mixing the transmitted signal with this reference range delayed signal, the modulation part of second order phase is removed. Hence, we can get the compressed fast time signal via FFT processing. τ_{ref} is the target echo delay at the reference range. The influence of the amplitude of the complex constant A is neglected in the following analysis. Substitute expression (4) into expression (6) to obtain the following formula:

$$s(t_r, t_a) = \exp \left[j \frac{4\pi}{\lambda} \left(R_0 + \frac{(R_0^2 - x_0^2)v_r^2}{R_0^3} t_a^2 \right) \right] \cdot \exp \left[j \frac{8\pi}{\lambda} \frac{(R_0^2 - x_0^2)v_r^2}{R_0^3} t_a t_r \right] \cdot \exp \left[j \frac{4\pi x_0}{\lambda R_0} v_r t_r \right] \cdot \exp \left[j \frac{4\pi x_0}{\lambda R_0} v_r t_a \right] \cdot \exp \left[j \frac{4\pi K_r}{c} (R_0 - R_{ref}) \left(t_r - \frac{2R_{ref}}{c} \right) \right] \cdot \exp \left[j \frac{4\pi K_r x_0}{c R_0} v_r t_a \left(t_r - \frac{2R_{ref}}{c} \right) \right] \cdot \exp \left[j \frac{4\pi K_r}{c} \frac{(R_0^2 - x_0^2)v_r^2}{R_0^3} t_a^2 \left(t_r - \frac{2R_{ref}}{c} \right) \right] \cdot \exp \left[-j \frac{4\pi K_r}{c^2} (R_0 - R_{ref})^2 \right] \quad (7)$$

In Formula (7), c is the speed of light and λ is wavelength. The range walk is mostly related to the moving target's range speed, and is caused by the coupling of the fast and slow time terms in the sixth exponential term of Formula (7). The range curvature is related to the azimuth velocity, which is the seventh exponential term. It is necessary to eliminate the coupling term of range fast time and azimuth slow time to remove the range walk of moving targets.

3.2. Analysis on Moving Target Range Migration

Based on the established signal model, the moving target motion characteristics are analyzed. According to the Chinese road speed limit, the maximum speed of urban roads should not exceed 50 km/h (13.8 m/s). Therefore, we simulate seven point targets with speeds of 13 m/s, 12 m/s, 11 m/s, 10 m/s, 9 m/s, 8 m/s, 7 m/s, respectively. We analyze the range walk and range curvature of seven targets within 0.2 s. Figure 4a shows the range walk of seven targets, and Figure 4b shows the their range curvature. We can find that the higher the speed, the more obvious the range walk and range curvature of the moving target. And, under same speed, the range walk is larger than the corresponding range curvature.

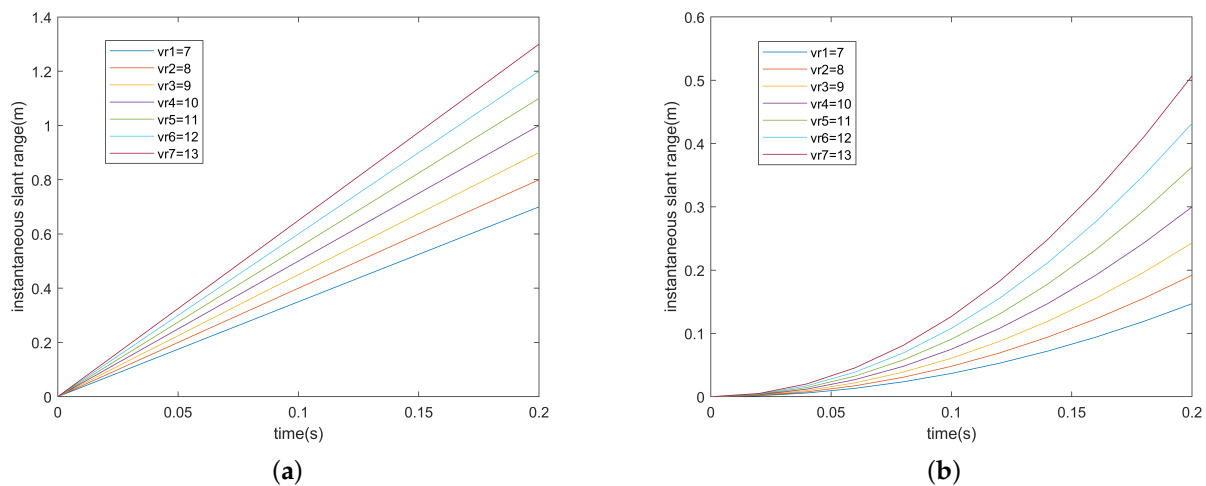


Figure 4. (a) Range walk. (b) Range curvature.

As shown in Figure 5, when the target speed is 50 km/h (13.8 m/s), the target range walk and range curvature are compared. At 0.2 s, the value of range walk is 1.11, the range curvature is 0.37. If a range resolution is 0.1 m, the range walk cross is 11 cells and the other one is 3 cells, which is three times larger than range curvature. Hence, the range walk is the dominant effect which needs to be removed. Therefore, we choose the first-order Keystone transformation to build the algorithm.

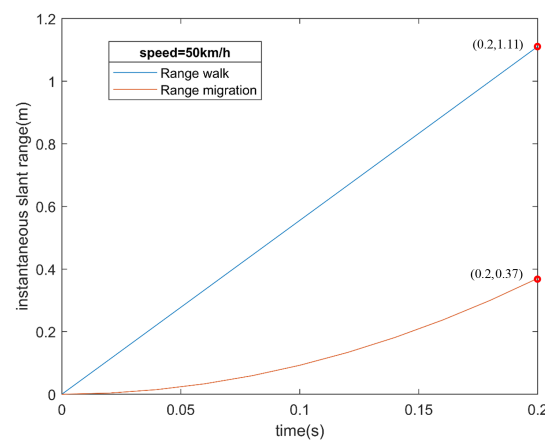


Figure 5. Range walk and range curvature of moving target at speed of 50 km/h.

4. Moving Target Detection Algorithm

4.1. The Traditional 2DFFT Algorithm

The traditional 2DFFT algorithm is widely used in moving target detection with FMCW radar system. Figure 6 shows the flow chart of the traditional algorithm. The key of the

algorithm is to convert the radar signal to the 2D frequency domain, and detect the moving target by analyzing the energy distribution [34,35]. The algorithm performs FFT operations to the radar raw data in the fast time dimension and slow time dimension; we can obtain the moving target motion parameters by detecting its location in the speed and range domains. After the 2DFFT transformation, constant false alarm rate (CFAR) detection is typically performed, followed by the use of the Density-Based Spatial Clustering of Applications with (DBSCAN) algorithm to eliminate false alarms near real target points. The CFAR detection algorithm can maintain a constant false alarm probability under different noise, clutter, and interference backgrounds, generating adaptive detection thresholds [36]. DBSCAN is a density-based clustering algorithm; it requires the configuration of two parameters: the neighborhood radius (Eps) and the minimum number of points (MinPts) [37].

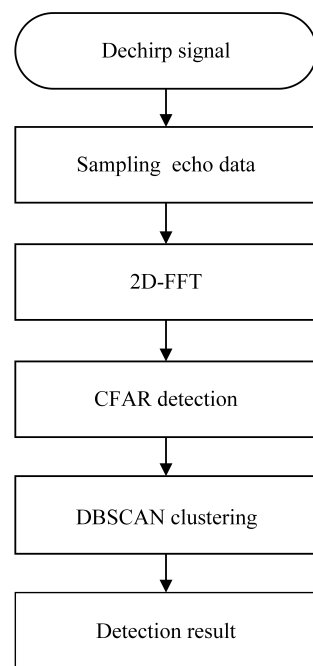


Figure 6. Flow chart of 2DFFT moving target detection algorithm.

The schematic diagram of the 2DFFT is shown in Figure 7. $\Delta t = 2R/c$ is the time delay of echo, R is the slant range from the radar to the target; $\Delta f = K \Delta t$ is the beat frequency, K is the slope. Firstly, the signal is sampled by AD repeatedly, and the data are stored in matrix. Then, FFT is performed on each row of the matrix to obtain the range compressed signal, and then FFT is performed on each column of the matrix to obtain the range-Doppler spectrum [7]. By analyzing the range-Doppler spectrum, the velocity estimation of the target can be obtained.

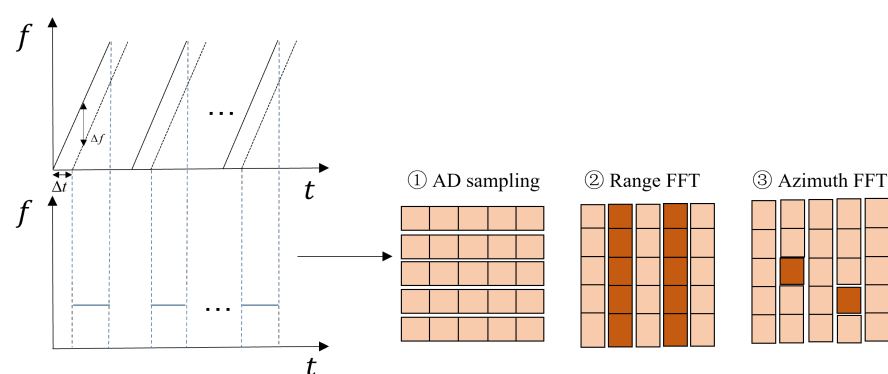


Figure 7. 2DFFT algorithm flow diagram.

The 2DFFT moving target detection algorithm has many advantages like simple and fast and less calculation. However, it assumes the target has a small range cell migration effect, i.e., it stays in a single range gate. This is not always valid in the traffic monitoring radar case due to the fact that the car has a relatively fast range speed. The range cell migration therefore cannot be ignored, which makes the 2DFFT algorithm's performance degrade. To improve the performance of the moving target detection, we introduce the keystone transformation to correct the target range walk before the 2DFFT step.

4.2. The Proposed Algorithm

Due to the movement of the target, the radar target echo will move across the range cell between pulses, resulting in 2D defocusing of the moving target. If the target range walk is not corrected, high-quality detection results cannot be obtained. To solve the above problems, it is necessary to remove the range walk. Figure 8 shows the proposed keystone-2DFFT algorithm's flow chart. The data are not equally sampled in azimuth time because of the features of the FMCW traffic monitoring radar transmitted signal in frame form (i.e., in one frame, it contains the uniformly sampled pulses, while there is a gap between frames). Therefore, it is necessary to sample the data before processing the echo. The sampled signal is then processed by the keystone transformation to remove the range walk, which improves the quality of the echo data. Then, the 2DFFT, CFAR detection, and DBSCAN Clustering are performed in turn to detect the moving targets.

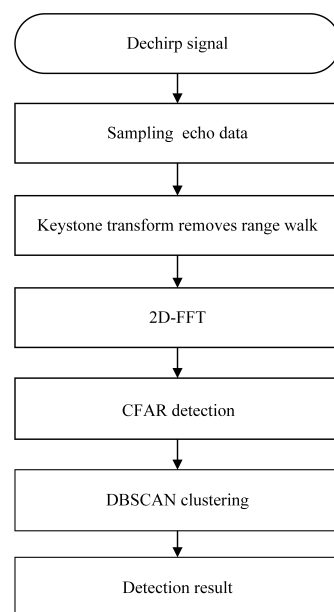


Figure 8. Flow chart of proposed detection algorithm.

The keystone transformation can also be called a cuneiform transform. It is a range walk correction technique applied in the field of SAR/ISAR, which can remove the range walk of moving targets without knowing the motion parameters of moving targets [38–40]. By defining the virtual azimuth slow time, the target signal is scaled in the slow time dimension. The higher the frequency, the larger the scaling amplitude. The traditional keystone transformation is applied to pulse radar systems. To perform a two-dimensional scaling transformation in the azimuthal slow-time and range-frequency plane for target echo, a virtual azimuth slow time τ is defined. The virtual azimuth slow time τ and the azimuth slow time t_a are designed to satisfy the equation:

$$t_a = \frac{f_c}{f_c + f_r} \tau \quad (8)$$

$\frac{f_c}{f_c + f_r}$ is called the scale factor. Due to matched filtering is typically conducted in range frequency domain, the range processing of the keystone is carried out as the f_r form. The above formula is valid for a pulse radar. However, in FMCW radars, the fast time pulse compression is based on the dechirp technique in the time domain. The range compression result is obtained after applying FFT on dechirped data. The identity of fast time t_r and f_r is switched under the FMCW radar condition. The proposed keystone transformation algorithm considers such an issue. The valid form is therefore shown as:

$$t_a = \frac{f_c}{f_c + K_r t_r} \tau \quad (9)$$

The principle of keystone transformation is shown in Figure 9. After keystone transformation, the signal $t_a - t_r$ is transformed from rectangle to inverted trapezoid.

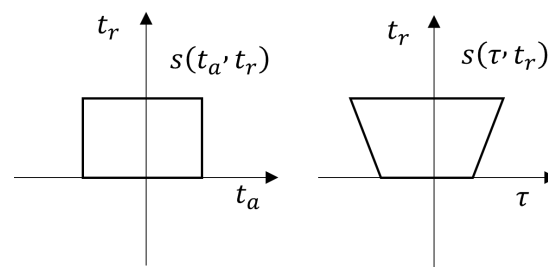


Figure 9. Keystone transformation schematic.

In Section 3.2, it can be found that the range walk effect is dominant. So, we only need to remove the range walk phenomenon. Therefore, we choose the first-order keystone transformation to remove the range walk of the moving target. This paper uses the Sinc interpolation method to realize the keystone transformation. From Equation (7), it can be seen that the coupling of the range fast time term and the azimuth slow time term causes the range walk. We rearrange Equation (7) to get a new expression:

$$\begin{aligned} s(t_r, t_a) = & \exp \left[j \frac{4\pi}{c} \left(\frac{x_0 v_r}{R_0} t_a \right) (f_c + K_r t_r) \right] \exp \left[j \frac{4\pi}{c} \left(\frac{(R_0^2 - x_0^2) v_r^2}{R_0^3} t_a^2 \right) (f_c + K_r t_r) \right] \\ & \exp \left[j \frac{4\pi}{c} (R_0 - R_{ref}) (f_c + K_r t_r) \right] \exp \left[j \frac{4\pi x_0}{\lambda R_0} v_r t_r \right] \exp \left[j \frac{8\pi (R_0^2 - x_0^2) v_r^2}{\lambda R_0^3} t_a t_r \right] \end{aligned} \quad (10)$$

The first exponential term is the range walk term. By substituting Equation (9) into Equation (10), the moving target signal can be obtained as:

$$\begin{aligned} s(t_r, t_a) = & \exp \left[j \frac{4\pi}{c} \frac{x_0 v_r}{R_0} f_c \tau \right] \exp \left[j \frac{4\pi}{c} \frac{(R_0^2 - x_0^2) v_r^2}{R_0^3} \frac{f_c^2}{f_c + K_r t_r} \tau^2 \right] \\ & \exp \left[j \frac{4\pi}{c} (R_0 - R_{ref}) (f_c + K_r t_r) \right] \exp \left[j \frac{4\pi x_0}{\lambda R_0} v_r t_r \right] \exp \left[j \frac{8\pi (R_0^2 - x_0^2) v_r^2}{\lambda R_0^3} t_a t_r \right] \end{aligned} \quad (11)$$

From Equation (11), it can be seen that the moving target range walk term $\exp \left[j \frac{4\pi}{c} \left(\frac{x_0 v_r}{R_0} t_a \right) (f_c + K_r t_r) \right]$ has been eliminated, which provides the basis for the following processing of the 2DFFT and the rest.

5. Experiment

To verify the effectiveness of the proposed detection algorithm and analyze its performance, this section gives point target simulation and real data experiments results. The experimental setup of simulation and real data and corresponding parameters are described in Section 2.

5.1. Point Target Simulation

To verify the effectiveness of the algorithm, the point target experiment is first carried out. Two cases of traditional 2DFFT (case 1) and the proposed keystone-2DFFT (case 2) are shown. Figure 10a is the signal after the range FFT without the application of the keystone transformation. It can be seen that the stationary target S1 does not appear to move across the range cell, while the moving target T1 crosses multiple range cells within azimuth slow time. Since the radar is static and moving targets only have range velocity, the range migration is mainly based on the range walk. Figure 10b shows the traditional 2DFFT algorithm's result; the stationary target S1 is focused and the moving target T1 is defocused.

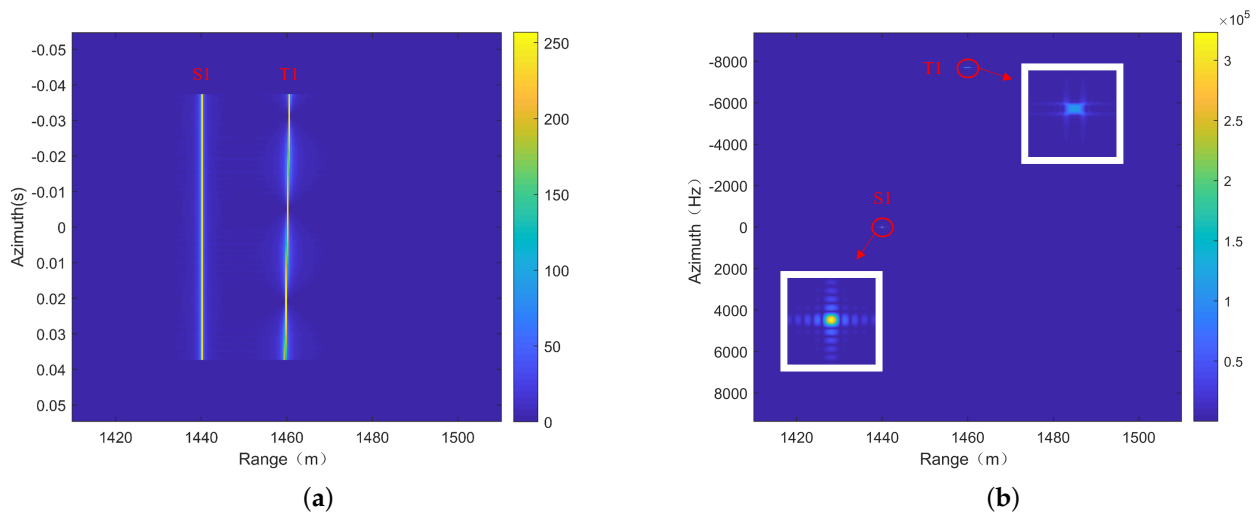


Figure 10. (a) Echo of range FFT without keystone transformation. (b) Original 2DFFT algorithm's results with defocused T1.

Now, the proposed method's result is shown. In Figure 11a, we use keystone transformation to remove the range walk of moving target T1. The keystone transformation is introduced before the 2DFFT transform to correct the range walk of the coupling of the range fast time term and the azimuth slow time term, and the corresponding 2DFFT result is shown in Figure 11b. Compared with Figure 10b, the original defocused moving target T1 has focused after processing by the proposed method. Therefore, it proves the effectiveness of the proposed method.

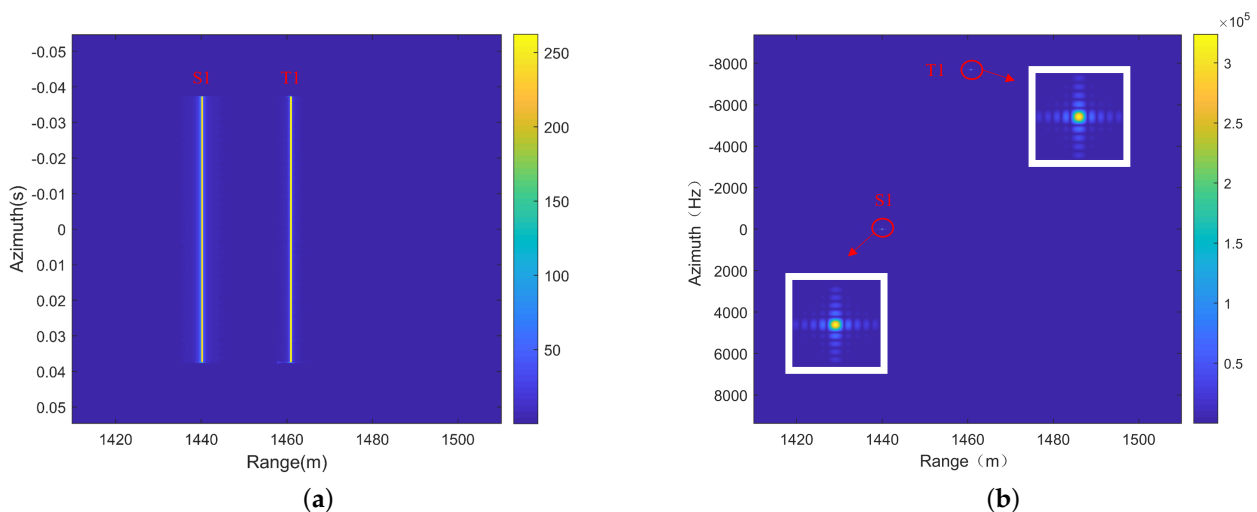


Figure 11. (a) Echo signal of range FFT after keystone transformation. (b) Proposed keystone-2DFFT algorithm's result with refocused T1.

5.1.1. Time-Bandwidth Product Analysis

To evaluate the performance, analysis of the algorithm with three different time-bandwidth products is carried out in this part. The parameters are set as follows: frequency modulation slope K_r is set as constant, the time bandwidth products (TBPs) are 132.61, 4034, and 13,261, and hence the signal bandwidths are 44.6 MHz, 146 MHz, and 446 MHz. Figure 12a–c show the Fourier transform results of the original signal under TBP of 132.61, 4034, and 13,261; we can see that the larger the TBP is, the larger the bandwidth and higher range resolution is. The more obvious range walk phenomenon can be seen. Figure 13a–c shows the results without range walk correction under TBP of 132.61, 4034, and 13,261. When TBP is larger, the resolution is increased and its tolerance on range is reduced. The resulting 2-dimensional defocusing become more severe. The range walk correction results under TBP of 132.61, 4034, and 13,261 are shown in Figure 14a–c. Due to removing the range walk, all results are all good. Therefore, when TBP is small, it may neglect the range walk phenomenon, but the larger the TBP, the more the range walk processing is needed. And the proposed method can handle the data under different TBP conditions.

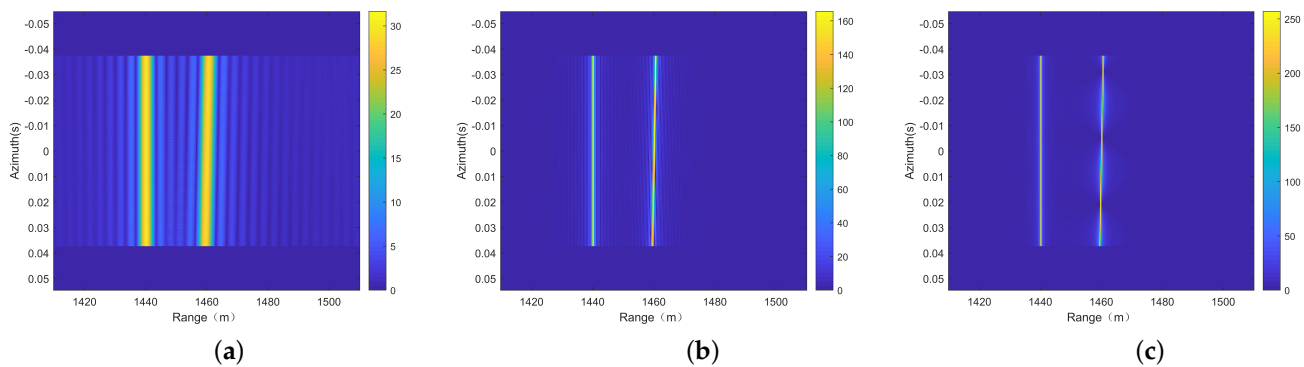


Figure 12. Comparison of echo of range FFT under the situations of TBP = 132.61, 4034, and 13,261 without keystone transformation. (a) TBP is 132.61. (b) TBP is 4034. (c) TBP is 13,261.

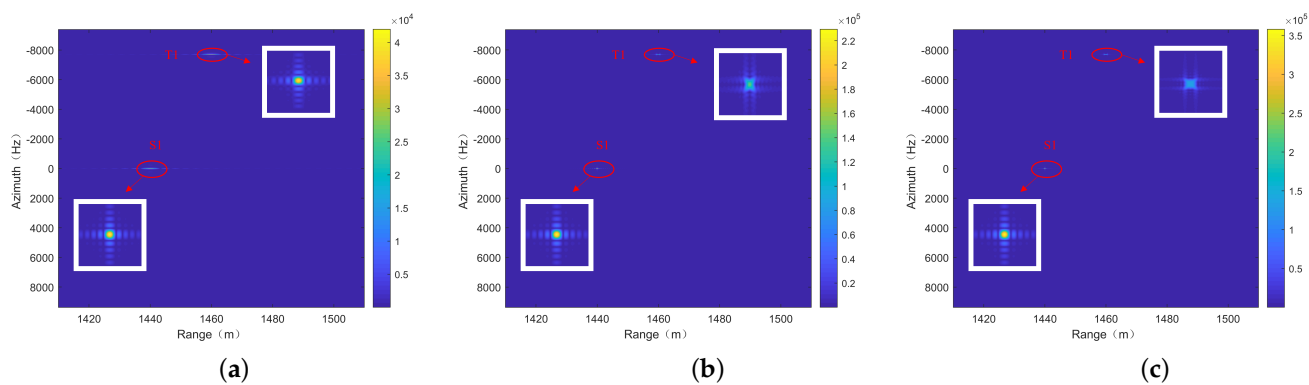


Figure 13. Results of traditional 2DFFT method under different TBPs. (a) TBP is 132.61. (b) TBP is 4034. (c) TBP is 13,261.

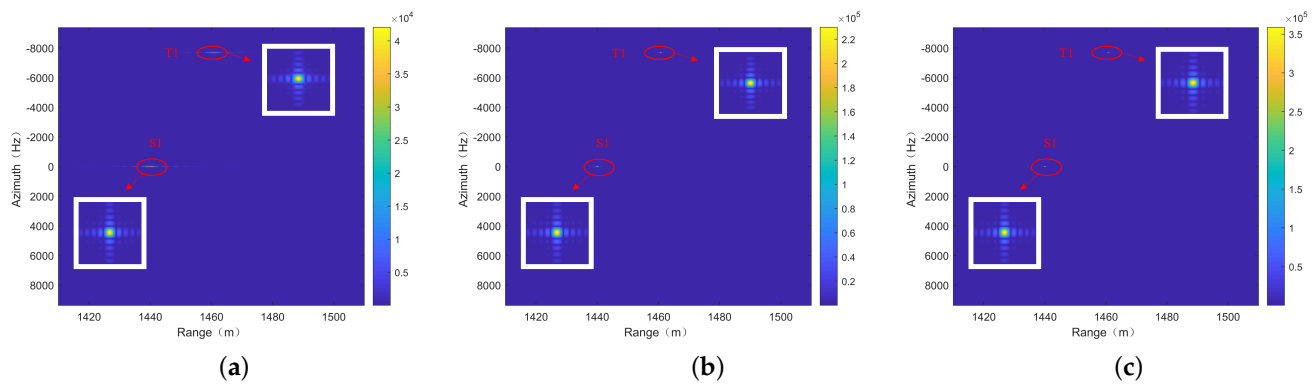


Figure 14. Results of proposed method under different TBP. (a) TPB is 132.61. (b) TPB is 4034. (c) TPB is 13,261.

5.1.2. Signal-to-Noise Ratio Analysis

To conduct analysis performance on the proposed method under different Signal-to-Noise Ratios (SNRs), simulations were performed with SNRs of -5 dB, 0 dB, and 5 dB. Figure 15a–c show the results of the range compressed signals at SNR -5 , 0 , and 5 dB. When SNR is -5 dB, the target signal can not be distinguished, they are all buried in the noise. The signal is barely seen when SNR is 0 dB. When SNR is 5 dB, the target signal can be clearly observed. Figure 16a–c shows the detection results of the proposed method when SNR is -5 dB, 0 dB, and 5 dB. The detection results are all good, even in the buried signal case.

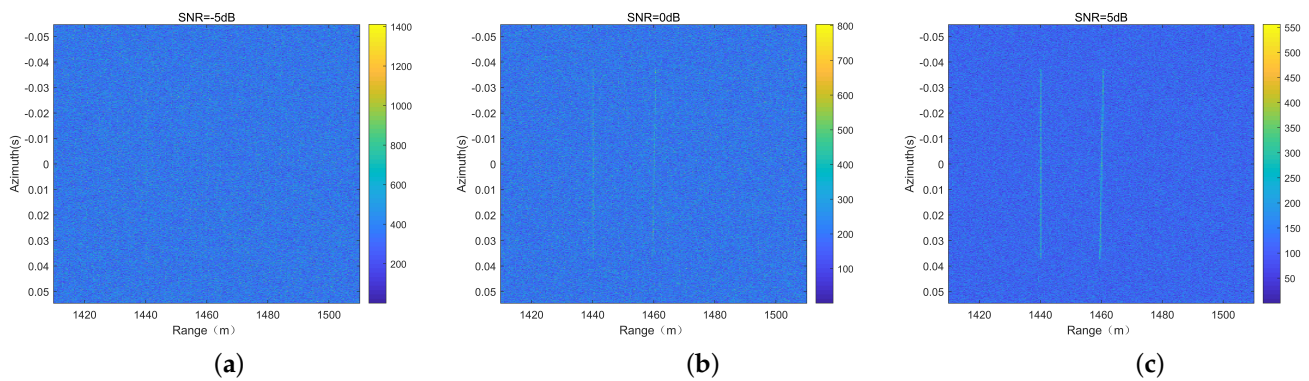


Figure 15. Comparison of echo of range FFT under the situations of SNR -5 , 0 , and 5 dB without keystone transformation. (a) SNR is -5 dB. (b) SNR is 0 dB. (c) SNR is 5 dB.

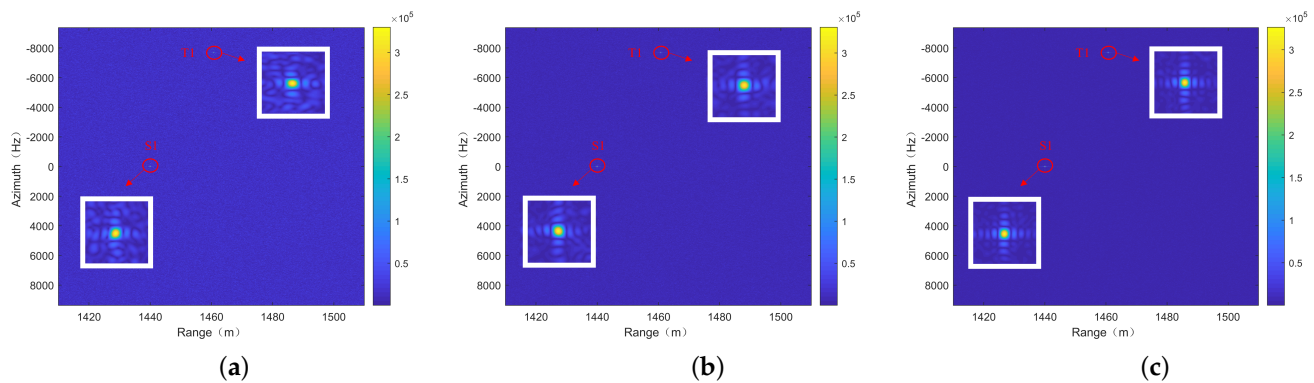


Figure 16. Results of proposed method under different SNRs. (a) SNR is -5 dB. (b) SNR is 0 dB. (c) SNR is 5 dB.

5.2. Real Data

Next is the real data experiment; 21 frames of the collected echo data were used for this experiment. Figure 17a is the 2DFFT algorithm's result. Taking the moving target T2 marked by the red circle in the figure as an example for analysis and processing, by observing the enlarged picture, we can find that the moving target signal is clearly defocused, it is across multiple range cells. Figure 17b shows the result of the original range compressed echo of moving target T2 in the real data. It is clear that moving target T2 has range walk.

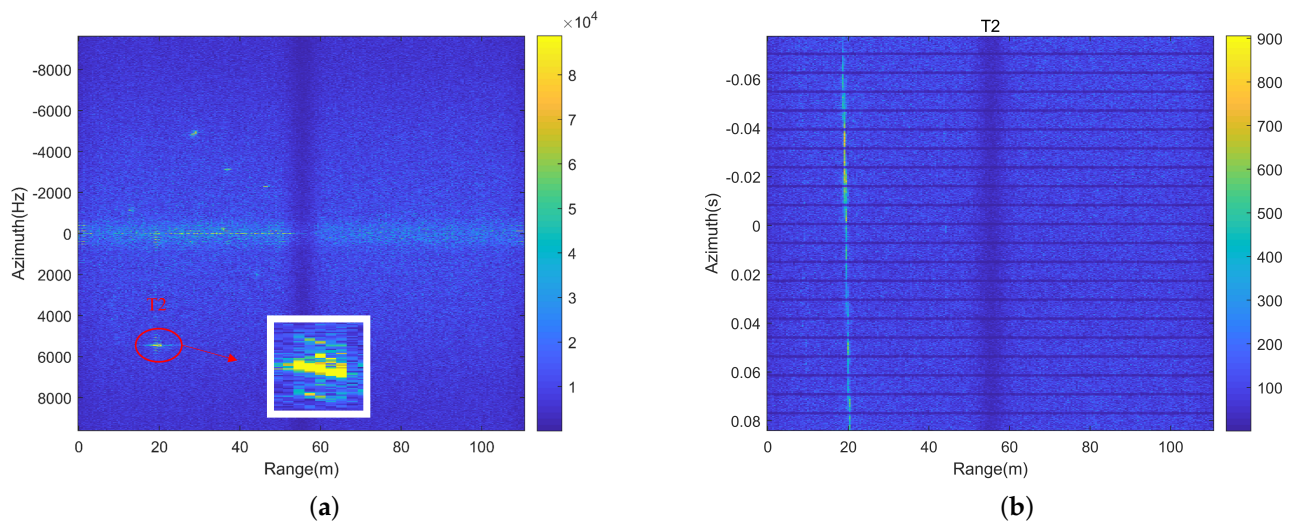


Figure 17. (a) Result of 2DFFT algorithm, T2 is the moving target in range-Doppler domain. (b) T2's range walk phenomenon with no processing.

Then, we perform the proposed method on real data. In Figure 18a, the keystone transformation is used to process the echo data, which eliminates the range walk of the moving vehicle. Figure 18b shows the result of keystone transformed echo after 2DFFT. It can be clearly seen that the T2 is focused with no range cell migration. We further analyze the SNR to show the proposed method has better performance than traditional algorithm. The SNR of the moving target T2 after the traditional algorithm in Figure 17a is 13.98 dB, while the SNR of the moving target after the proposed algorithm in Figure 18b is 18.66 dB. The improvement of SNR is 4.68 dB, which proves the effectiveness of the proposed method in traffic monitoring radar.

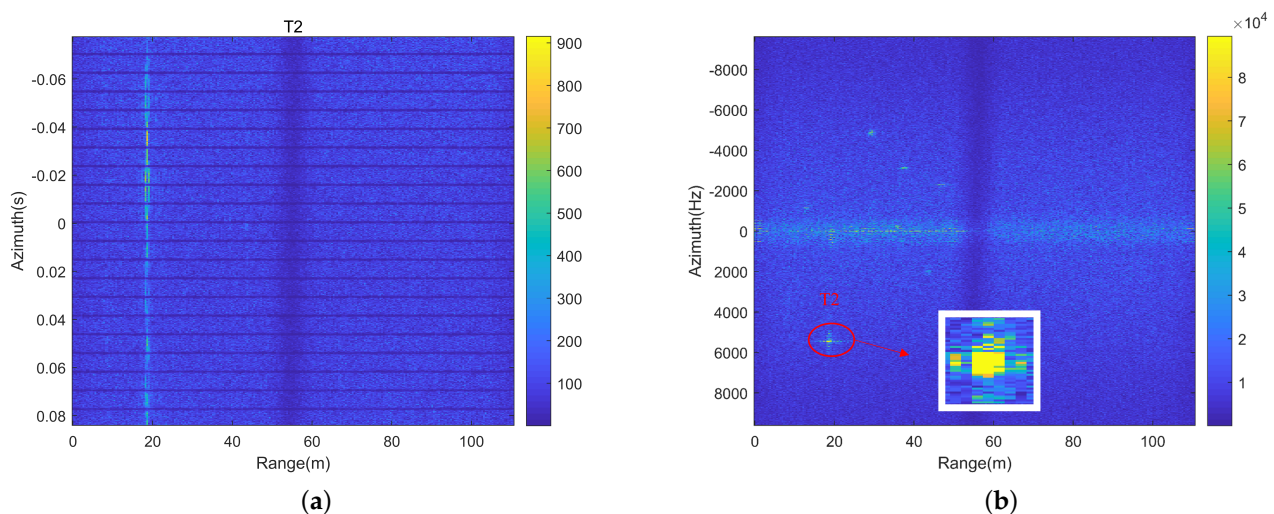


Figure 18. (a) Result of T2's range walk removal via proposed method. (b) Result of proposed algorithm, T2 is focused in range-Doppler domain.

6. Conclusions

Millimeter wave radar has the advantage of all-day and all-weather capability for detection, speed measurement and identification of moving targets in traffic. It plays an important role in urban traffic flow monitoring and traffic safety monitoring. The conventional 2DFFT algorithm performs target detection in the range-Doppler domain. Due to it needing multiple pulses, the target motion will induce the range walk phenomenon. In the traffic monitoring scenario, the range walk is the key factor in performance degradation of detection, which leads to the decrease of target energy and the performance degradation of target detection and speed measurement. This paper proposes a moving vehicle detection algorithm based on Keystone-2DFFT for traffic scene. Firstly, this paper constructs and analyzes the FMCW moving target signal model under the traffic monitoring scenario. The traditional 2DFFT moving target detection algorithm is briefly introduced. Then, based on mentioned signal model, an improved moving vehicle detection algorithm based on Keystone-2DFFT transform is proposed. The method first inputs the echo, then the range walk is removed by keystone transformation. The keystone transformation is achieved via Sinc interpolation. Next, transform data into range-Doppler domain to perform detection and speed estimation. The algorithm is verified by simulation data and real data.

Future work includes further improving the proposed method and developing a moving vehicle imaging method.

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